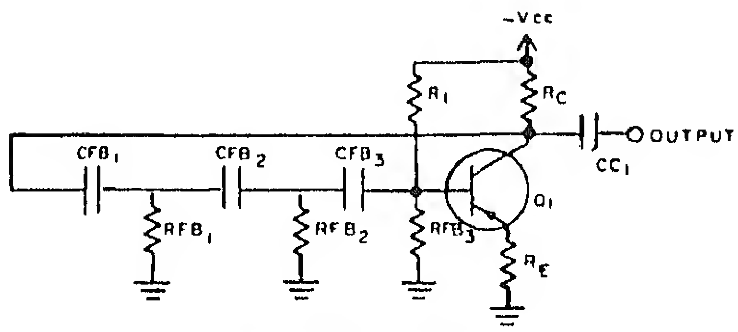
STUDENT GUIDE

FOR

ADVANCED FIRST-TERM AVIONICS COURSE

CLASS A1

C-100-2010



UNIT III

PREPARED BY

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MILLINGTON, TENNESSEE

CNTT-M1696

PREPARED FOR

CHIEF OF NAVAL TECHNICAL TRAINING

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FOREWORD

The purpose of this Student's Guide is to assist you through Special Circuits, UNIT III, of the Advanced First-Term Avionics Course. The proper use of this guide will sharpen your theoretical troubleshooting skills and also aid you in laboratory situations later on in the AFTA course, particularly in the RADAR Unit.

The table of contents lists the page numbers for the class schedule, homework schedule, information sheets, and notetaking sheets that will further enhance your abilities and skills as electronics technicians.

SAFETY NOTICE

As a Marine or Navy electronics technician, you will be required to perform safe and efficient maintenance on various types of electronic equipment. Not only your life, but the lives of many others will depend on your being conscious of safety at all times. It is the responsibility of all Navy and Marine Corps personnel to prevent accidents. This can be done if everyone is conscientious about safety and observes all precautions when performing maintenance of any type.

HOW TO USE THIS STUDENT'S GUIDE

This Student's Guide has been prepared for you to use while you are attending the Advanced First-Term Avionics (A1) Course. Ample space has been provide for taking notes on the required lesson information. Remember, when you are in class, the information being provided by your instructor is information you will need in performing your Navy or Marine job.

This volume contains the following:

1. Information Sheets for some topics, to provide additional material for more difficult lessons.
2. Notetaking Sheets containing lesson topic outlines with illustrations and ample space for personal notetaking.

UNIT III CLASS SCHEDULE

Unit III is two weeks long and starts in the middle of the fifth day of the fourth week. The periods run from 157 to 236 with the last period finishing half-way through the last day of the sixth week.

The schedule is as follows:

TOPIC NO.	TYPE	PERIOD	TOPIC
FOURTH WEEK			
Fifth Day			
2.17	Class	153	Unit/Module Test: Written Examination
		154	
		155	
		156	
3.1	Class	157	Power Supply Rectifiers
		158	
		159	
		160	
FIFTH WEEK			
First Day			
3.1	Class	161	Power Supply Rectifiers
		162	
		163	
		164	
3.2	Classs	165	Power Supply Filters
		166	
		167	
		168	
Second Day			
3.2	Class	169	Power Supply Filters
		170	
		171	
		172	
3.3	Class	173	Power Supply Regulators
		174	
		175	
		176	

TOPIC NO.	TYPE	PERIOD	TOPIC
Third Day			
3.3	Class	177	Power Supply Regulat‹
		178	
		179	Power Supply Regulators
		180	
		181	
		182	
3.4	Class	183	Audio-Frequency Power Amplifiers
		184	
Fourth Day			
3.4	Class	185	Audio-Frequency Power Amplifiers
		186	
		187	
		188	
3.5	Class	189	Oscillators
		190	
		191	
		192	
Fifth Day			
3.5	Class	193	Oscillators
		194	
		195	
		196	
	Class	197	Unit/Module Test: Written Examination
		199	
3.6	Class	200	Nonsinusodial Waveforms
SIXTH WEEK			
First Day			
3.6	Class	201	Nonsinusodial Waveforms
3.7	Class	202	Wave-Shaping Circuits
		203	
		204	
		205	
		206	
3.8	Class	207	Sweep Generators
		208	

TOPIC NO.	TYPE	PERIOD	TOPIC
3.8	Class	209 210 211 212 213 214 215 216	Sweep Generators
Third Day			
3.9	Class	217 218	Limiters
3.10	Class	219 220	Clampers
3.11	Class	221 222	Blocking Oscillators
3.12	Class	223 224	Multivibrators
Fourth Day			
3.12	Class	225 226 227 228 229 230 231 232	Multivibrators
Fifth Day			
	Class	233 234 235 236	Unit/Module Test: Written Examination
4.1	Class	237 238	Duty Preference Cards
4.2	Class	239	Radio Frequency Power Amplifiers

UNIT III HOMEWORK SCHEDULE

All of the assignment sheets listed below shall be turned in when due. Each assignment sheet will be checked by an instructor for completeness and correctness. Failure to turn in an assignment sheet could result in disciplinary action.

Assignment Sheet	Period Due
3.1.1A	169
3.2.2A	177
3.3.1A	185
3.4.1A	193
3.5.1A	196
3.6.1A	209
3.7.1A	209
3.8.1A	217
3.9.1A	225
3.10.1A	225
3.11.1A	225
3.12.1A	233

TERMINAL OBJECTIVE

5.0 Mathematically ANALYZE operating characteristics of given basic semiconductor power supplies by solving problems in terms of voltage, impedance, current, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 099967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

ENABLING OBJECTIVES

5.1. Mathematically ANALYZE the operating characteristics of given semiconductor rectifier and filter circuits of SOLVING problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

5.2. Mathematicalally ANALYZE the operating characteristics of given semiconductor voltage regulator circuits by SOLVING problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP- 000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

TERMINAL OBJECTIVE

6.0. Mathematically ANALYZE the operating characteristics of given semiconductor amplifiers and oscillators by solving problems in terms of voltage, current, impedance and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

ENABLING OBJECTIVES

6.1. Mathematically ANALYZE the operating characteristics of given semiconductor AF amplifiers by SOLVING problems in terms of voltage, current, impedance, power, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

6.2. Mathematically ANALYZE the operating characteristics of given semiconductor oscillators by SOLVING problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

6.3. Mathematically ANALYZE the operating characteristics of crystal controlled oscillators by SOLVING problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronics Circuits Manual, NAVSEA 0967-LP-000-0-120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

TERMINAL OBJECTIVE

7.0. Mathematically ANALYZE the operating characteristics of given basic semiconductor waveshaping circuits by solving problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

ENABLING OBJECTIVES

7.1. Mathematically ANALYZE the operating characteristics of given basic semiconductor pulse-forming circuits by SOLVING problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronic Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

7.2. Mathematically ANALYZE the operating characteristics of given semiconductdor relaxation oscillators by SOLVING problems in terms of voltage, current, impedance, and frequency. Response must be in accordance with Electronics Circuits Manual, NAVSEA 0967-LP-000-0120 series. Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

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INFORMATION SHEET 3.1.1I

POWER SUPPLY RECTIFIERS

INTRODUCTION

Rectifiers are used to convert an alternating current to a direct current to provide the power required for the operation of electrical and electronic equipment. Several types of rectifiers exist, and selection is based upon the requirements of the equipment. The d-c output of a power supply can be either positive or negative, depending upon the circuit design, but it will always be a pulsating d-c voltage (ripple) and will require some type of filtering.

REFERENCES

1. Basic Electronics, Vol. I. NAVPERS 10087-C. Chapter 5.

2. Electronic Circuits. NAVSEA 0967-LP-000-0120. Chapter 2, pages 2-1 through 2-74.

3. Slurzberg, Morris, and William Osterheld. Essentials of Radio-Electronics. Second Edition. New York: McGraw-Hill Book Company, Inc., 1961. Chapter 9.

4. Slurzberg, Morris, and William Osterheld, Essentials of Communication Electronics. Third Edition. McGraw-Hill Book Company, Inc., 1973, Chapter 7.

INFORMATION

SINE WAVE VALUES

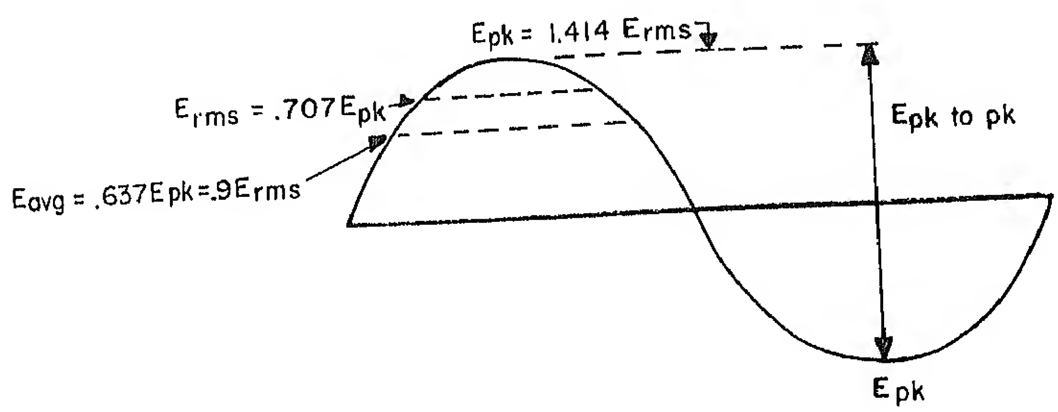


FIGURE 1

In figure 1, the sine-wave values indicated are the ones most often used. These are the peak (E_{pk}) value, the rms (E_{rms}) value (also called effective value), the average (E_{avg}) value, and the peak-to-peak (E_{pk-pk}) value. Peak, rms, and average voltage are values of an alternation of the cycle. An understanding of their relationships to each other is vital to understanding the power supply theory.

The relationships of voltages are as follows:

1. E_{pk} is the maximum instantaneous value of one alternation of current: one-half of the peak-to-peak value.

2. E_{rms} is the effective value, which is 70.7 percent of the peak value. RMS, or effective, is the a-c value of voltage that will produce the same heating effect as a d-c voltage.

3. E_{avg} is the average voltage value of one alternation of current and is equal to 63.7 percent of the peak value or 90 percent of the rms value.

Symbols Used In Connection with Rectifier Circuits

1. E_{sec}--the rms voltage induced into the secondary winding of the power transformer.

2. $E_{sec\ pk}$--the peak voltage induced into the secondary winding of the power transformer.

3. I_{sec}--the rms current in the secondary winding, the diode or diodes, and the load.

4. E_{d-c} --the average value of the waveform at the cathode(s) of the rectifier for a positive supply and at the anode(s) for a negative supply.

5. I_{d-c} --the average current through the rectifier circuit.

6. PIV (peak inverse voltage)--the peak reverse bias voltage applied to the diode, which cuts off conduction. This is not to be confused with the manufacturer's rating, which indicates the maximum value for the diode. Peak inverse voltages are the voltages actually encountered under circuit-operating conditions.

Half-wave rectifier (single-phase)

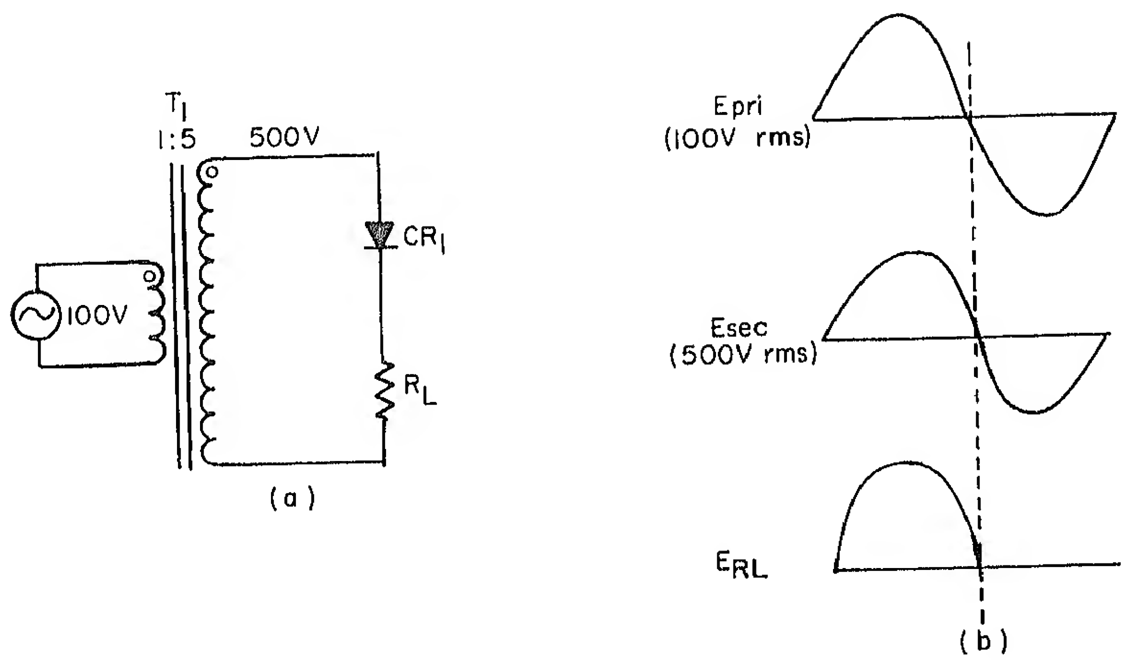


FIGURE 2

Figure 2a shows the basic half-wave rectifier circuit working into a resistive load. The rms value of the primary voltage is indicated to be 100 volts. The transformer has a one-to-five turns ratio; therefore, the rms voltage in the secondary is 500 volts. During the positive-going alternation, at the top of T_1's secondary, diode CR_1 will be in a forward-biased condition. This will allow current to flow through the secondary circuit, from the cathode to the anode of the diode, through the secondary winding (acting as a source), through R_L (negative at the bottom to positive at the top), returning to the cathode and completing the loop. Because of current flowing through R_L (the load resistance) a voltage will be developed across it. On the next alternation, the top of T_1 will become negative and diode CR_1 will be in a reverse-biased condition. During this period, there will effectively be no current in the circuit and no voltage developed across R_L. These conditions are shown in figure 2b.

When determining the voltage in the output (across R_L), several conditions will be considered.

1. Assume that the impedance of the diode when conducting is negligible (1 Ω).

2. Consider that the secondary winding is acting as a source, with negligible internal resistance.

3. The diode under reverse-bias conditions offers an infinite impedance (1,000,000 Ω).

4. These conditions are idealistic but will give close approximations of actual conditions.

Using the potentials shown in figure 2, now reevaluate the various components of the waveforms. In figure 3, the top waveform, labeled "E_{sec}," has an rms value of 500 volts. Its peak value will then be 1.414 times the rms voltage, or 707 volts. The average of one alternation is 0.637 of the peak, or 0.9 of the rms voltage, and is equal to 450 volts. The second waveform shows the current through the circuit that will flow only when the diode is forward-biased. There is no current on the voltage alternation that reverse-biases the diode. During the alternation, when current is flowing, a voltage pulse is developed across R_L. This pulse at the top of R_L has a peak value of 707 volts, an rms value of 500 volts, and an average value equal to 450 volts. Assuming no voltage drop across the diode or the secondary winding, the voltages are across R_L. These values of voltage are for one alternation. During the next alternation, the voltage across R_L is zero.

The d-c voltage on R_L is the average of the two alternations. Since the average value of the voltage alternation on the conducting half cycle is 450 volts and on the nonconducting half cycle is 0 volt, the over-all average would be $\frac{450V + 0V}{2}$ = 225 volts.

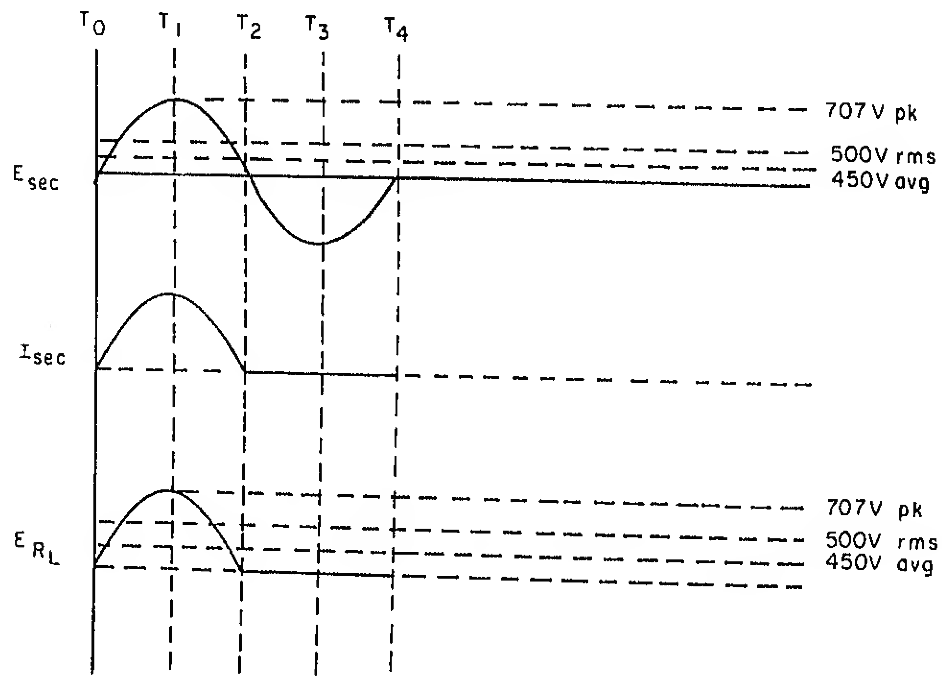


FIGURE 3

The d-c voltage across the load resistance is 225 volts. The fraction of the peak secondary voltage that is converted to d-c is $\frac{225\ V}{707\ V} = 0.318$. Therefore, $E_{d-c} = 0.318\ E_{sec\ pk}$.

Likewise, the decimal part of the rms secondary voltage that is converted to d-c is $E_{d-c} = \frac{225\ V}{500\ V} = 0.45\ E_{sec}$.

Determining current in the output

The current flows through the entire circuit when the diode is in a forward-biased condition. The voltage across R_L is one half-cycle of a sine wave, with a peak and an rms voltage. These voltages along with R_L determine the current.

The peak current is $\frac{E_{sec\ pk}}{R_L}$ and rms current is $\frac{E_{sec}}{R_L}$.

The d-c current can be found just as easily by $\frac{E_{d-c}}{R_L}$.

Formulas for various values of current then are:

1. $I_{sec\ pk} = \frac{E_{sec\ pk}}{R_L}$

2. $I_{sec} = \frac{E_{sec}}{R_L}$

3. $I_{d-c} = \frac{E_{d-c}}{R_L} = 0.318\ I_{sec\ pk}$, or $0.45\ I_{sec}$

Peak inverse voltage

Peak inverse voltage (PIV) is the peak of the voltage applied to the diode that is inverse to its conduction (also known as "the peak reverse-biasing voltage").

Refer back to figure 2. The alternation that is negative at the top of the secondary winding will cause the diode to be cut off or reverse-biased. Since no current goes through the circuit when the diode is reverse-biased, an infinite or nearly infinite imped must exist. This resistance in series with R_L causes all th applied voltage to be dropped across the diode. This means maximum negative voltage on the anode of the diode is the p the secondary waveform. The peak inverse voltage of a half rectifier with a resistive load is then equal in amplitude peak of the secondary voltage ($E_{sec\ pk}$).

Full-wave rectifier circuit (single-phase)

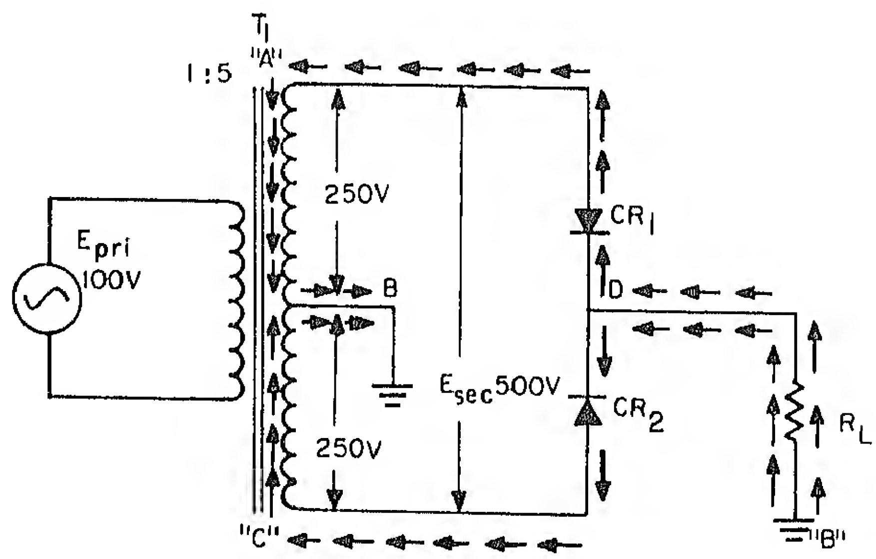


FIGURE 4

The illustration in figure 4 of a full-wave rectifier circuit shows the various relationships of rms voltage within the power transformer. The primary voltage is 100 volts. The turns ratio of the transformer (primary to full secondary) is 1 to 5. The rms voltage induced into the full secondary is 500 volts. The secondary winding has its center tap at ground; therefore, one-half of the 500-volt E_{sec} is from the top of the primary winding to ground, and the other half is from the bottom to ground. Diode CR_1 conducts when the top of the secondary winding is positive in relation to ground; and at the same time, diode CR_2 is cut off because the bottom of the secondary winding is negative in respect to ground. The conduction path for CR_1 is from cathode to anode to point "A", from point "A" to point"B" at the center tap, from the center tap through R_L, and back to the cathode, thus completing the loop. The voltage causing current through this loop is one-half the voltage induced into the entire secondary winding.

On the next alternation, point "A" is negative in respect to ground, cutting off CR_1. The voltage at point "C" is positive in respect to ground, causing CR_2 to conduct. The conduction path for CR_2 is from cathode to anode to point "C", from point "C" to the center tap at point "B", from point "B" through R_L and back to the cathode of CR_2. Once again, the conduction is caused by one-half of the total voltage being induced into the secondary winding.

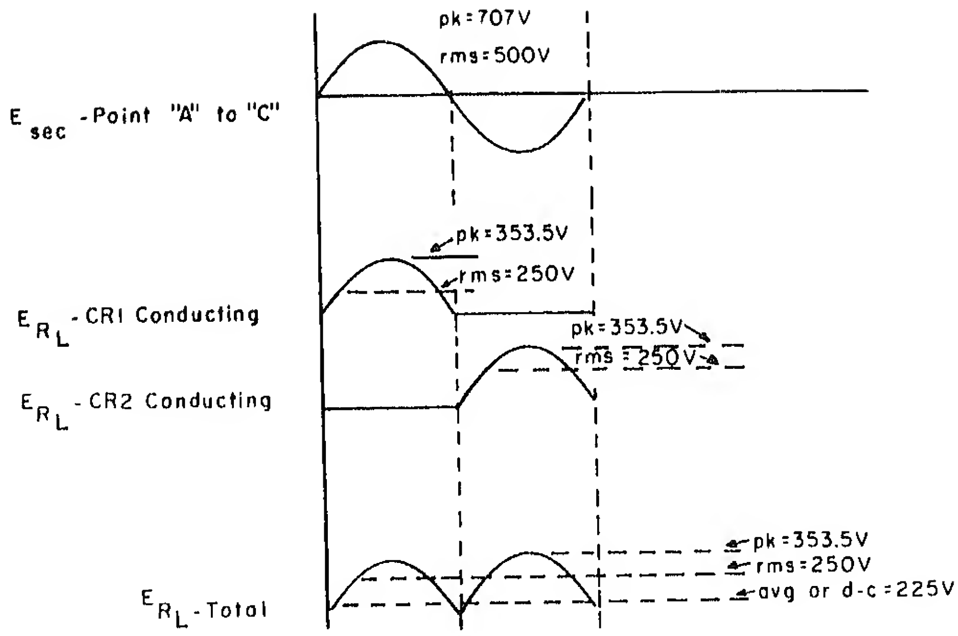


FIGURE 5

Figure 5 is a waveform analysis of the determination of output voltage. The top waveform shows the voltage induced into the entire secondary winding.

When the first alternation causes point A to be positive in respect to ground, CR_1 conducts. This voltage is developed across CR_1 and R_L. Assuming the conducting resistance of CR_1 and the resistance of the primary winding to be negligible, the total voltage that is causing CR_1 to conduct is felt across R_L. This is shown by the second waveform. The voltage developed across R_L during this time is one-half of the secondary voltage. During the same time period, the bottom of the transformer secondary is negative relative to ground and all the voltage in the bottom half of the secondary is developed across CR_2, leaving none to be developed across R_L. This is illustrated by the third waveform in figure 5.

In the next alternation, CR_1 is cut off and all the voltage from the top half of the secondary winding is developed across CR_1. CR_2 is conducting during this alternation, developing the voltage from the bottom half of the transformer secondary across R_L.

The fourth waveform, the combined waveforms from the conduction of both diodes across R_L, is shown in figure 5. This waveform shows the peak of each alternation to be equal to one-half the peak voltage on the secondary winding ($1/2\ E_{sec}$ pk). The voltage on each alternation is one-half the rms voltage on the secondary winding. The average, or d-c voltage, is equal to the average of each alternation.

Since the alternations across R_L do not go both above and below ground, but rather are only going above ground, the waveform is not a sine wave and has an average value other than zero. In this case, the overall average of both alternations is equal to

$$\frac{0.637\ E_{R_L\ pk} + 0.637\ E_{R_L\ pk}}{2}, \text{ or } 0.637\ E_{R_L\ pk}$$

The formulas for computing d-c voltages are stated in relation to the voltage induced into the entire secondary winding. To explain this, remember that the peak voltage across R_L is equal to one-half the peak voltage on the secondary winding (1/2 $E_{sec\ pk}$).

$$E_{avg} = E_{d-c} = 0.637\ E_{R_L\ pk}$$

and $$E_{R_L\ pk} = 1/2\ E_{sec\ pk}$$

Therefore, $$E_{d-c} = 0.637 \times 1/2\ E_{sec\ pk}$$

$$= \frac{0.637\ E_{sec\ pk}}{2}$$

$$= 0.318\ E_{sec\ pk}$$

$$E_{avg} = E_{d-c} = 0.9\ E_{R_L}$$

and $$E_{R_L} = 1/2\ E_{sec}$$

Therefore, $$E_{d-c} = 0.9 \times 1/2\ E_{sec}$$

$$= \frac{0.9\ E_{sec}}{2}$$

$$= 0.45\ E_{sec}$$

The E_{d-c} from the full-wave rectifier with a resistive load is calculated in the same manner as that of the half-wave rectifier.

The advantage of the basic full-wave rectifier circuit over the basic half-wave rectifier circuit does not lie in its d-c voltage output, since both rectifier circuits (using transformers with the same applied voltages and the same turns ratios) give the same d-c outputs. The full-wave rectifier is more expensive to build, as it requires two diodes rather than just one, and the power transformer requires a center-tapped secondary. To determine the advantage, look at the output voltages of both rectifiers.

Figure 6 is a comparison of the waveforms on the transformer. The outputs of the half-wave and the full-wave rectifiers are shown; both rectifiers have an alternating waveform in their outputs. The variation in the waveforms from the rectifiers is known as ripple. Ripple voltage varies above and below the d-c voltage levels. The d-c voltage levels are the averages. The peak of the ripple from the half-wave rectifier is twice the magnitude of the peak ripple from the full-wave rectifier. The frequency of the ripple from the full-wave is twice the frequency of the ripple from the half-wave. The ripple is in the form of an alternating wave and is undesirable in the d-c output. In most rectifiers, the ripple is filtered in the output to give almost a pure d-c.

The advantage of the full-wave rectifier is that the ripple output is easier to filter because of its lower amplitude and higher frequency.

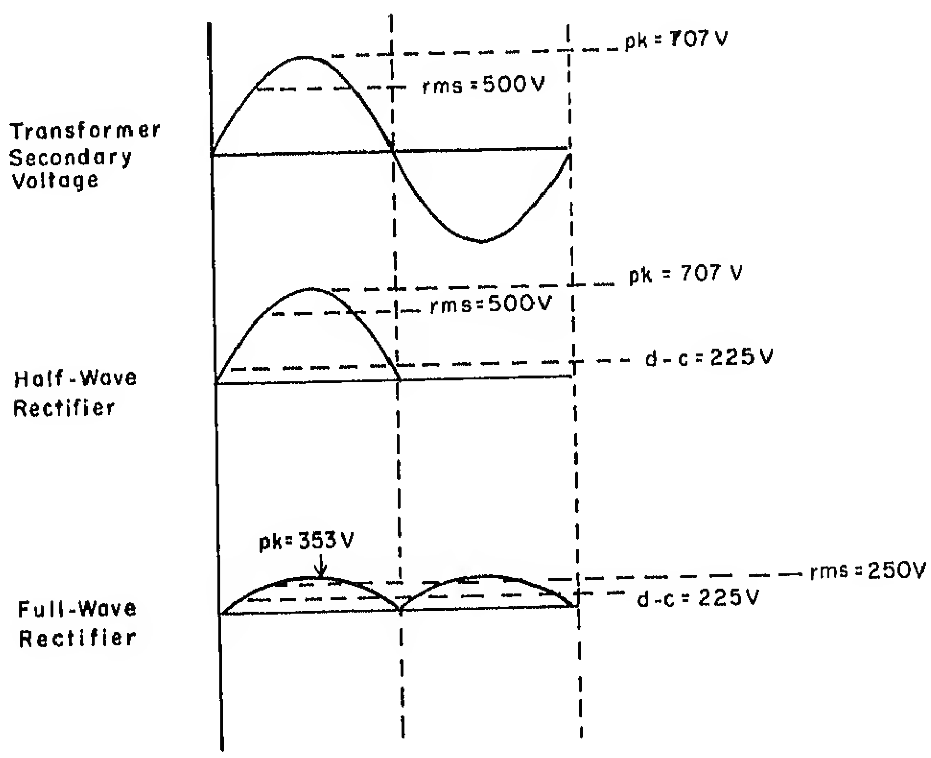


FIGURE 6

To determine the peak inverse voltage encountered by a diode in a full-wave rectifier circuit with a resistive load, study figure 7. In figure 7, CR_1 is cut off and CR_2 is conducting. At the instant that CR_2 has the peak positive voltage on its anode, CR_1 has a peak negative voltage on its anode. The peak value on the anode of CR_2 is 1/2 $E_{sec\ pk}$. Conduction of CR_2 causes a peak voltage to be developed across R_L (positive at the top) equal to 1/2 $E_{sec\ pk}$. The top of R_L is also at the cathode of CR_1, which places this peak voltage on its cathode. At the same time, the peak negative voltage on its anode is equal to 1/2 $E_{sec\ pk}$.

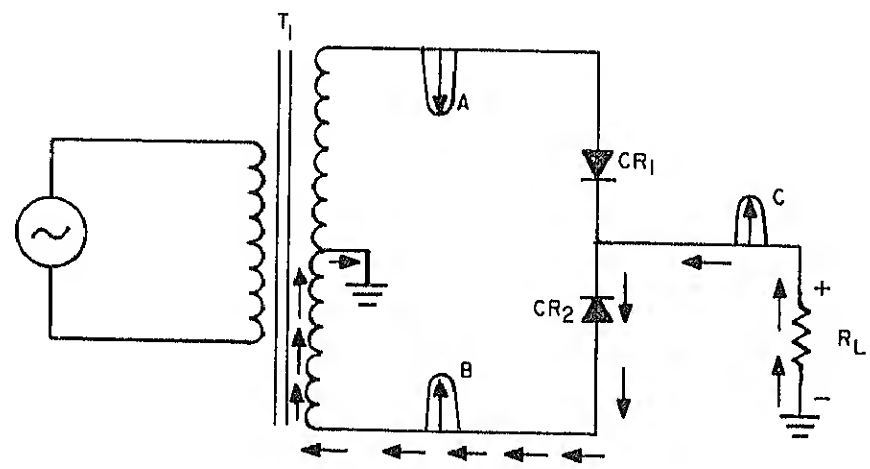


FIGURE 7

'oltage across the nonconducting CR_1 is equal to the sum of aks or to the full peak secondary voltage.

Full-wave bridge rectifier

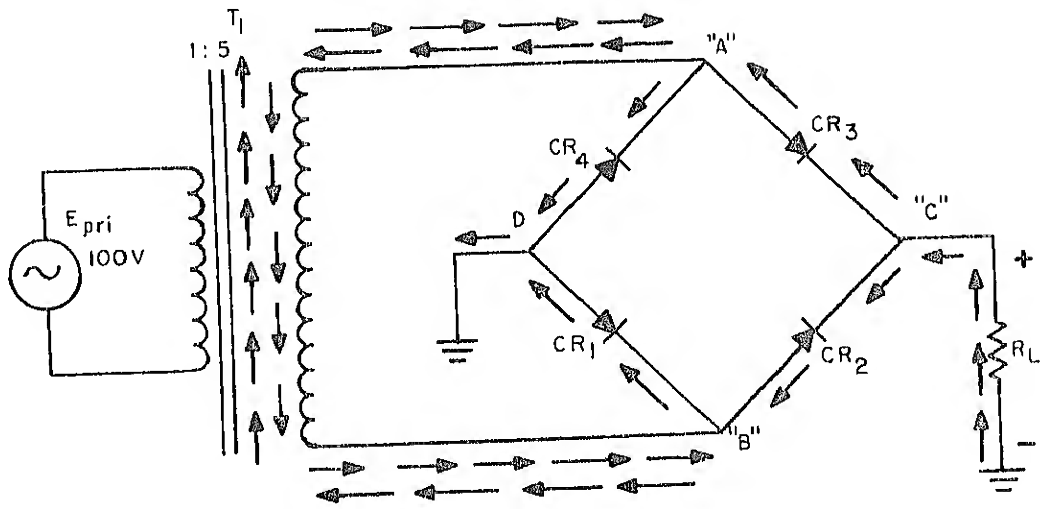


FIGURE 8

Figure 8 shows the basic bridge rectifier circuit. This circuit (like the others) is using a power transformer with a 1 to 5 turns ratio. There is no center tap on the transformer secondary. Paths for current are through are two diodes an alternation rather than one.

To understand basic operation, first look at the half cycle that is positive at the top of the transformer secondary (point "A" in figure 8); point "B" is negative. At point "A", CR_3 is conducting and CR_4 is cut off. The conduction path for CR_3 is from cathode to anode to point "A", from point "A" through the secondary winding (top to bottom) to point "B", from point "B" (point "B" is negative) through CR_1 to ground, from ground up through R_L, and back to the starting point. On the next half cycle, point "B" is positive and point "A" is negative. Conduction path is from cathode of CR_2 to point "B", from point "B" through the secondary winding (bottom to top) to point "A", from point "A" through CR_4 to ground, from ground up through R_L, and return to the starting point. On one half cycle, CR_1 and CR_3 conduct, while CR_2 and CR_4 are cut off; and on the other half cycle, the opposite set of diodes conduct. In either case, a positive voltage is developed at the top of R_L.

Output voltage of the bridge rectifier, with a purely resistive load, is computed as shown in figure 9. The top wave form is the a-c voltage at point "A" (top of the secondary winding). The next waveform shows the voltage developed across R_L as a result of conduction of CR_1 and CR_3. When point "A" is positive, these two diodes conduct, developing a voltage alternation equal to peak voltage induced into the entire secondary winding. Since the peak voltages are equal, the rms values of E_{R_L} and E_{sec} must also be equal on this alternation. When the top of the secondary winding is negative, CR_1 and CR_3 are cut off and produce zero voltage across R_L. At the same time, however, CR_2 and CR_4 are conducting and develop a waveform of voltage across R_L, with a peak that is positive at the top of R_L and is equal to the peak voltage induced into the secondary winding.

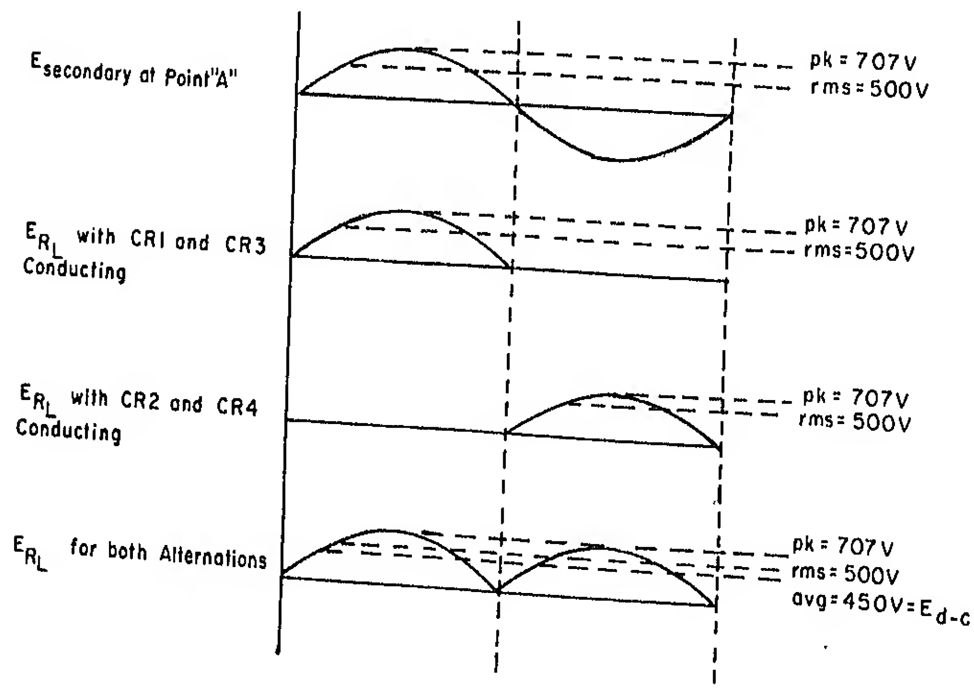


FIGURE 9

The complete voltage wave form caused by the conduction of both sets of diodes across R_L is shown at the bottom of figure 9. Note that in each alternation the peak amplitude of E_{R_L} is equal to the peak of the voltage induced into the entire secondary winding, instead of just 1/2 of the winding: the entire secondary winding is across the conduction path of the two conducting diodes on both half cycles. The d-c output voltage is the average of the waveform developed across R_L. Since the peak voltage of each alternation is equal to the peak of the secondary voltage and the average, or d-c value, of each alternation is equal to 0.637 times its peak, the average value of the waveform across R_L is equal to

$\frac{0.637\ E_{R_L}\ pk + 0.637\ E_{R_L}\ pk}{2}$ which is 0.637 E_{R_L} pk. Since E_{R_L} pk then E_{d-c} is equal to 0.637 E_{sec} pk. The average voltage equals 0.9 of the rms value, so E_{d-c} equals 0.9 E_{sec}.

Briefly review figures 2, 4, and 8 and observe the transformer turns ratio in all three cases. All transformers used have a 1 to 5 turns ratio, with a 100-volt rms applied to the primary. The half wave and the full wave have a d-c output voltage of 225 volts, while the bridge has a d-c output voltage of 450 volts, or twice the magnitude for the same power transformer. This is one advantage of the bridge rectifier. We will see another advantage in the following discussion.

The peak inverse voltage encountered by the nonconducting diodes in the bridge circuit may be relized by considering the action of the circuit in figure 8 at the instant the peak positive voltage is at point "A". At this instant, CR_1 and CR_3 are conducting at their maximum. Keep in mind the conducting diodes effectively act as a short circuit: there is no difference in potential between cathode and anode. The peak of the voltage at point "A" is felt at the top of R_L, because of the conduction of CR_3; and point "B" is at ground, because of the conduction of CR_1.

A redrawn circuit, as shown in figure 10, shows the effective condition on CR_2 and CR_4 at this time. Figure 10 shows the circuit when the diodes are conducting. The cathode of CR_4 is at point "A", which has the secondary peak positive voltage applied. The anode of CR_4 is at ground. The full voltage on CR_4, preventing conduction, is the peak of the secondary voltage. Then the PIV for CR_4 is equal to E_{sec} pk. The other nonconducting diode (CR_2), at the same instant, has its anode grounded, because the conduction of CR_1 effectively places ground at point "B". With respect to the cathode of CR_1, a positive peak voltage develops at the top of R_L. It was determined earlier that the peak voltage on R_L (E_{R_L} pk) is equal to the peak secondary voltage (E_{sec} pk). The cathode of CR_2 at this instant is positive by E_{sec} pk, and its anode is at ground. The conclusion to be drawn is that the peak inverse voltage encountered by each nonconducting diode in the circuit is equal to E_{sec} pk.

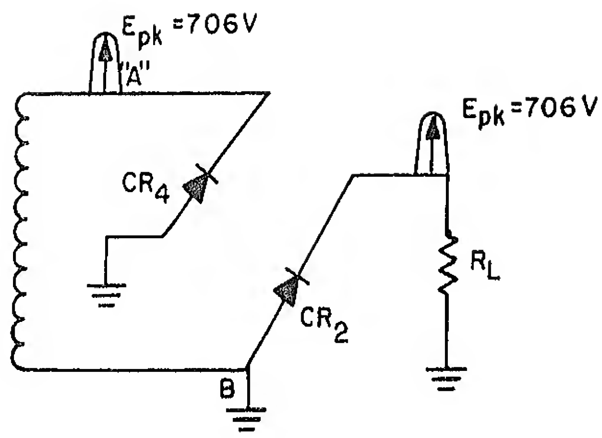


FIGURE 10

To understand the advantage in its proper perspective, recall that for a transformer with a given turns ratio, the d-c output voltage of the bridge rectifier would be twice that of either the half wave or full wave. To produce the same amount of d-c as the bridge, the half wave and the full wave would both require either twice the a-c applied to the primary or a transformer with twice the turns ratio. In either, the peak a-c voltage on the secondary winding would be twice that of the bridge transformer secondary. The PIV's encountered by the diodes in all three basic rectifier circuits (using resistive loads) are $E_{sec\ pk}$. Therefore, for a given d-c OUTPUT level, the nonconducting diodes in a bridge rectifier encounter one-half the PIV that the nonconducting diodes in the other two rectifier circuits encounter.

Full-wave voltage doubler

/e voltage doubler is capable of delivering to a load a that is twice the peak value of the a-c applied voltage. is used in situations when the load requires a higher than is available with the existing transformer, or high d-c potential is required without the expense of rmer. When the current requirement of the load is is impractical. It is therefore used for high voltage under light-load conditions. Figure 11 shows two schematics commonly used for the full-wave doubler.

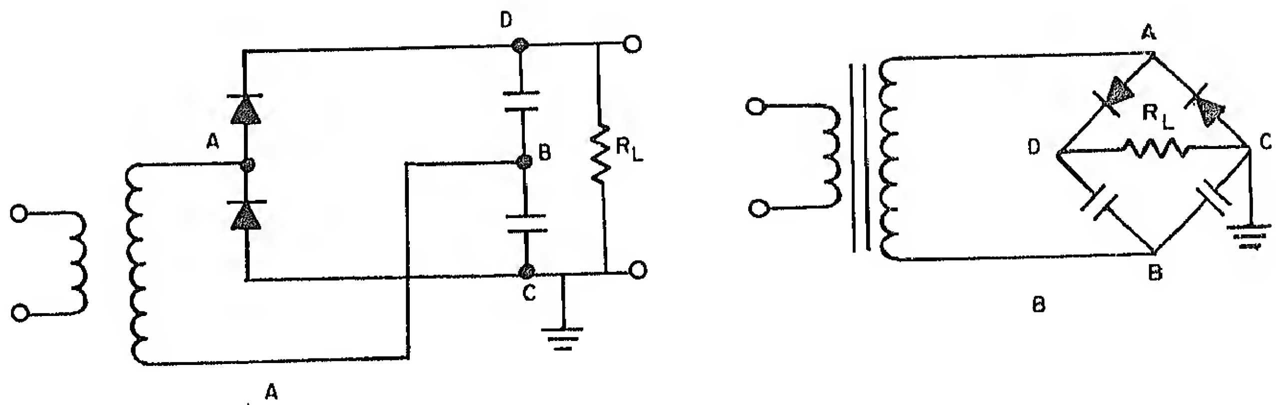


FIGURE 11

Figure 12 is the same circuit shown in figure 11b. To understand the circuit action, it is first necessary to understand that a capacitor will charge to the peak of the voltage applied to it.

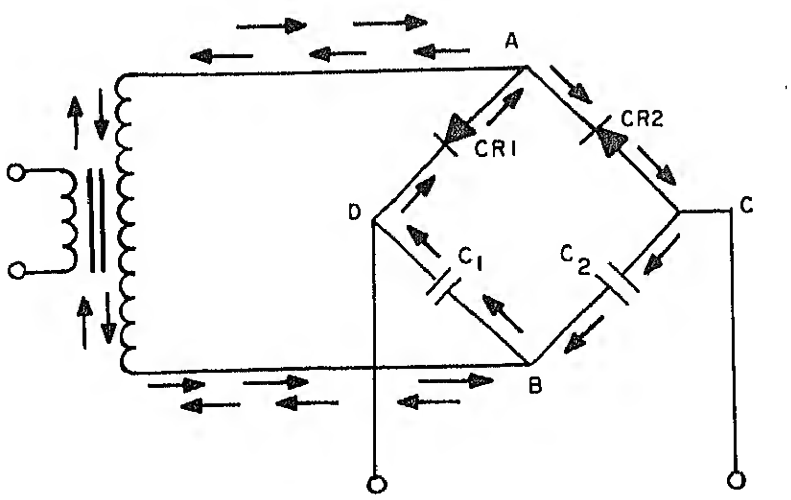


FIGURE 12

The final output is actually achieved after several cycles of input a-c voltage. As shown in figure 12, when the positive half cycle is applied to point "A", CR_1 conducts. The conduction path is from the top plate of C_1 (drawing electrons from that plate) through CR_1 (cathode to anode) to point "A", from point "A", through the secondary winding (top to bottom) to point "B", and from point "B" to the bottom plate of C_1. Since electrons are moving from the top plate of C_1 to accumulate on the bottom plate, the capacitor is charged negative at the bottom plate to positive at the top plate. The voltage to which C_1 will charge (neglecting voltage losses across the diode and secondary winding) will be equal to the peak of the applied voltage ($E_{sec\ pk}$). On the next alternation, point "A" will be negative and CR_2 will conduct. The conduction path is from the bottom plate of C_2, to point "B", from point "B", through the secondary winding (bottom to top), to point "A", and from point "A", through CR_2 (cathode to anode) to the top plate of C_2. This charges C_2, negative at the top to positive at the bottom, to a voltage equal to $E_{sec\ pk}$.

As shown in figure 12, the output of the doubler is fed between point "C" and point "D", which places C_1 and C_2 in series with one another and in parallel with the load. Since the charged capacitors aid each other in series and the voltage of each is approximately equal to $E_{sec\ pk}$, the d-c output voltage is equal to approximately twice the peak of the secondary voltage, or $E_{d-c} = E_{sec\ pk}$. In actual practice, the d-c output voltage is slightly less than 2 $E_{sec\ pk}$ because the capacitors will discharge a small amount through the load during the time the charging diodes are not conducting. They will be recharged on the alternation when their respective charging diodes conduct. This produces a small-amplitude ripple voltage. The d-c output voltage is equal to the average of this ripple voltage. The math necessary to compute the ripple amplitude is beyond the scope of this course, but for our purpose, E_{d-c} = 2 $E_{sec\ pk}$ is close enough.

Figure 13 shows a waveform analysis of the actual doubler operation. The top waveform represents the secondary a-c voltage. The next waveform is the d-c output voltage and the ripple varying around it. The positive peak of the ripple amplitude occurs at a voltage equal to 2 $E_{sec\ pk}$. The peak of the ripple waveform is from its average (E_{d-c}) to 2 $E_{sec\ pk}$. The value of the d-c voltage is actually the difference between 2 $E_{sec\ pk}$ and $E_{rip\ pk}$. For most approximations, this difference is small enough to be neglected.

The PIV that the nonconducting diode encounters in the circuit is twice the peak value of the secondary voltage. Refer to figure 12 and note the current conditions when one diode is conducting. Start with point "A" at its peak positive value of applied voltage with CR_1 conducting. At this time, CR_1 places a short (for all practical purposes) between points "A" and "D" because of its conduction.

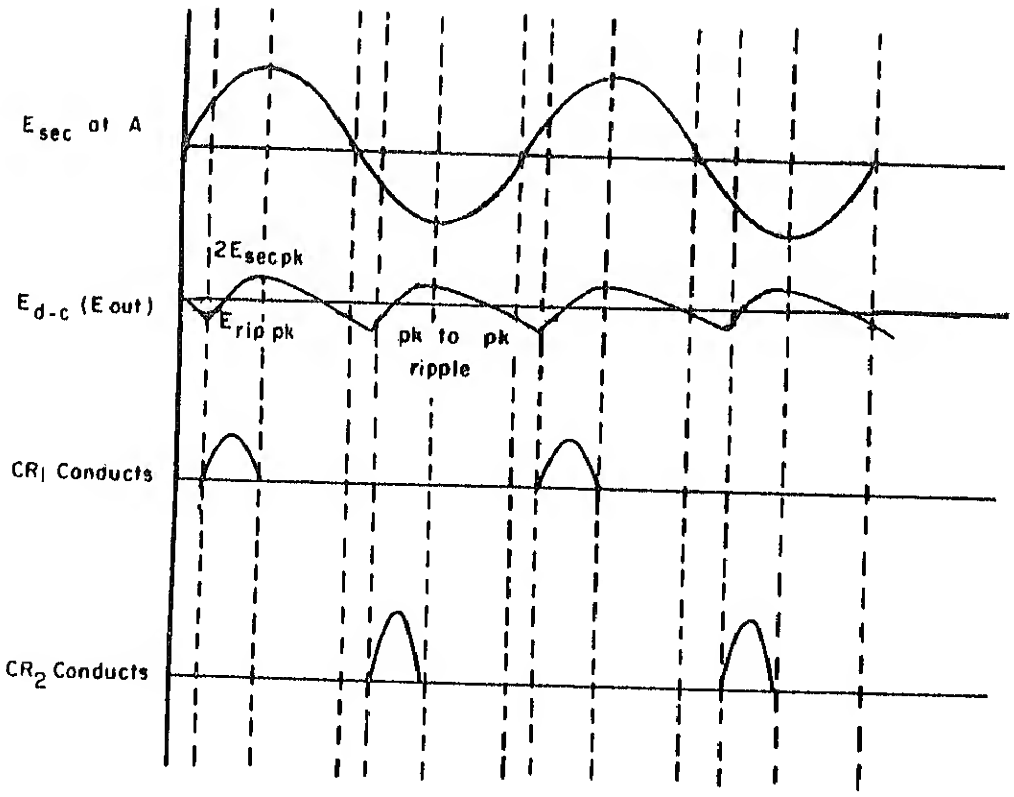


FIGURE 13

Figure 14 shows this condition. This places the cathode of CR_2 (the non-conducting diode) at point "D" and its anode at point "C", or directly across C_1 and C_2. Since the voltages on the two capacitors add up to 2 $E_{sec\ pk}$ and their polarities apply reverse voltage to CR_2, PIV = 2 $E_{sec\ pk}$.

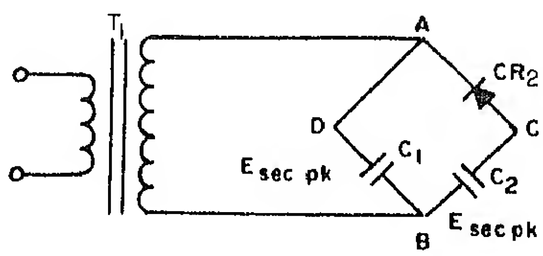


FIGURE 14

Remember that under actual circuit conditions, a ripple voltage is produced because the capacitors change their charge during the time their respective charging diodes are cut off (with the capacitors discharging slightly through the load). The actual d-c value on the load is less than 2 $E_{sec\ pk}$. The amount by which the d-c is less depends upon how much the capacitors can discharge before they are recharged. This is to say, the amplitude of the ripple voltage depends on how much they change their charge. The more they change their charge, the higher the amplitude of the ripple voltage.

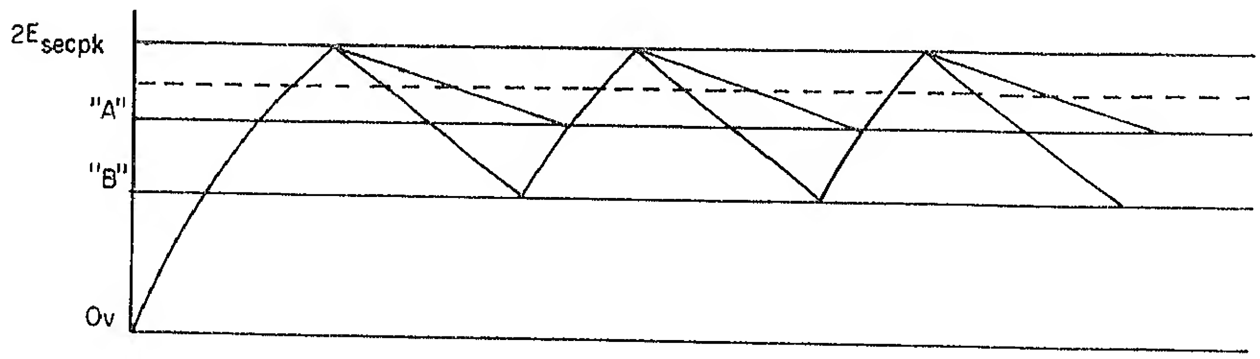


FIGURE 15

As shown in figure 15, the ripple peak-to-peak amplitude with one set of doubler capacitors is from the level of 2 $E_{sec\ pk}$ to level "A". The dotted line between shows the average, or d-c level. The peak-to-peak amplitude of the ripple, using the same doubler and load, but with a smaller set of capacitors, is from the level of 2 $E_{sec\ pk}$ to the level "B". The average of d-c level for this ripple is approximately at the level marked "A". This change in amplitude of ripple is caused mainly by the RC time of the capacitors and the load resistance. The larger the capacitors, the longer the RC time, and the less the capacitors will discharge between the times their respective charging diodes conduct. The less the capacitors discharge, the lower the ripple amplitude, and the higher the actual d-c output level.

Therefore, since T = RC, if C increases, time increases, ripple
e decreases, and d-c voltage to the load increases. There
ting factor, however, to the maximum size of capacitors
used. To charge a capacitor, a charging current must
is, a quantity of electrons must move from one plate to
late. Q = CE (where Q is a quantity of electrons, C is
ance in μF, and E is the voltage across the capacitor).
voltage, the larger C is, the larger Q will be, and the
charging current will be, or the larger the capacitance,
the charging current will be for a given voltage. If the
rrent exceeds the peak current ratings of the charging
diodes will be destroyed. Therefore:

1. The higher the capacity of the capacitors in the doubler, the higher the actual d-c output will be.

2. The amount of capacitance must be limited by the peak current rating of the diodes.

Half-wave voltage doubler

The half-wave doubler (or line doubler) meets most of the same conditions as the full-wave doubler. The d-c output equals 2 $E_{sec\ pk}$ (approx.). The PIV encountered by the diodes equals 2 $E_{sec\ pk}$, and the values of capacitance are limited by the peak current ratings of the charging diodes. The difference is mainly in the circuit configuration.

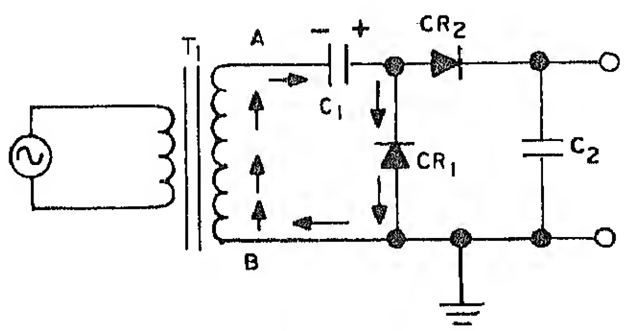


FIGURE 16

Figure 16 shows the circuit configuration for the half-wave doubler. When CR_1 conducts, C_1 is charged. This occurs when the induced voltage at point "B" is on its positive alternation. The conduction path of CR_1 is from the right-hand plate of C_1 through CR_1, to point "B", from point "B" through the secondary winding (bottom to top), to point "A", and from point "A" to the left-hand plate of C_1 (charging it negative at the left to positive on the right). It charges to the peak of the applied voltage. On the next alternation, with point "B" negative, the secondary voltage and the voltage on C_1 are series aiding. This causes CR_2 to conduct. The conduction path of CR_2 is from the top plate of C_2, through CR_2, to the right-hand plate of C_1, from the left-hand plate of C_1 to point "A", from point "A" through the secondary winding (top to bottom) to point "B", from point "B" to the bottom plate of C_2, which charges C_2 to the sum of the transformer's secondary peak voltage and the voltage across C_1. This voltage sum is equal to 2 $E_{sec\ pk}$ (approx.). The output voltage from this doubler is dropped across C_2. Since C_2 charges to 2 $E_{sec\ pk}$, E_{d-c} = 2 $E_{sec\ pk}$.

When compared with the half-wave doubler, the full wave's output capacitors are recharged each half cycle rather than once each full cycle as with the half-wave doubler. Ripple amplitude is lower and therefore produces a higher d-c output. The one decided disadvantage, however, of the full-wave doubler is that the common point for its output must be above chassis ground, unless an isolation transformer is used. This is not the case with the half-wave doubler. Therefore, the half-wave doubler is considered less hazardous to maintenance personnel.

Three-phase, half-wave (three-phase star) rectifier

Application. The three-phase, half-wave star- or wye-connected rectifier is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c power requirements exceed 1 kilowatt. The rectifier circuit can be arranged to furnish negative or positive high-voltage output to the load.

Characteristics of three-phase, half-wave rectifier

1. Input to circuit is three-phase a-c; output is d-c with amplitude of ripple voltage less than that for a single-phase rectifier.

2. Uses three semiconductor rectifiers (single, multiple, or stacked units).

3. Output is relatively easy to filter; d-c output ripple frequency is equal to three times the primary line-voltage frequency.

4. Has good regulation characteristics.

5. Circuit provides either positive- or negative-polarity output voltage.

6. Uses multiphase power transformer with star- or wye-connected secondary windings; primary windings may be either delta- or wye-connected.

Circuit analysis

The three-phase, half-wave (three-phase star) rectifier is
əst type of three-phase rectifier circuit. Fundamentally,
ifier circuit is three single-phase, half-wave rectifier
each rectifier operating from one phase of a three-phase
ɜ sharing a common load. The voltages induced in the
ər secondary windings differ in phase by 120°; thus, each
rectifier conducts for 120° of the complete input cycle
ibutes one-third of the d-c current suplied to the load.
flow through the load in pulses--one pulse for every other
ə of the impressed voltage in each of the three phases--
, the output voltage has a ripple frequency that is three
frequency of the a-c source. These relations are shown in

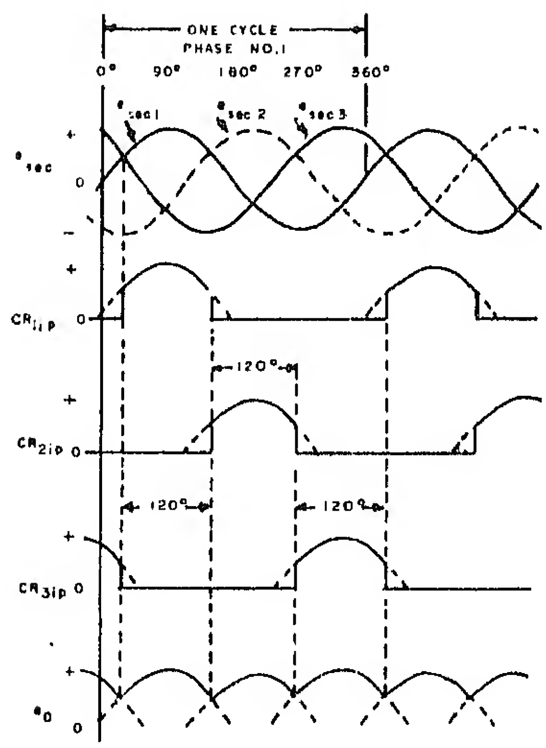
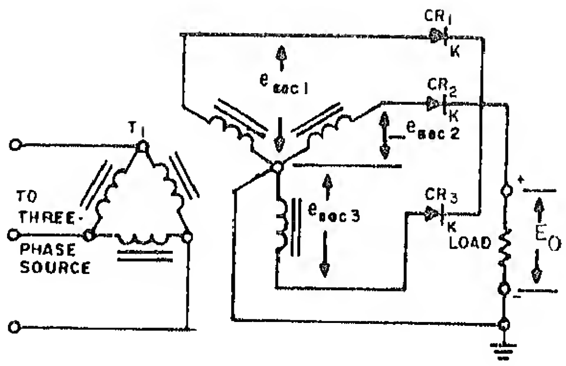


FIGURE 17.--Three-phase, half-wave rectifier waveforms.

Circuit operation. A basic three-phase, half-wave rectifier is illustrated in figure 18. The circuit uses a three-phase transformer, T_1, to step up the alternating source voltage to a high value in the star- or wye-connected secondaries. The primary windings of transformer, T_1, are shown delta-connected, although in some instances the primary windings may be wye-connected. Rectifiers CR_1, CR_2, and CR_3 are connected to the high-voltage secondary winding. The load is connected between the junction point of the wye-connected secondary windings and the common connection of the three rectifiers.



Basic Three-Phase, Half-Wave (Three-Phase Star)
Rectifier Circuit

FIGURE 18

In the circuit illustrated, either terminal of the load can be placed at ground potential, depending upon whether a positive or negative d-c output is desired. However, it is good design practice for the d-c output terminal associated with the junction of the wye-connected secondaries to be grounded; in this circuit, the secondary-to-core insulation need not be as great as it would be if the secondary windings were above ground by the amount of the d-c ouput voltage. When a negative high-voltage d-c supply is required, it is common practice to keep the junction of the wye-connected secondaries at ground (chassis) potential and to reverse the connections to the rectifiers (CR_1, CR_2, and CR_3). In figure 18, the output polarity across the load will be opposite that shown. The semiconductor rectifiers, CR_1, CR_2, and CR_3, are made up of several rectifiers in series to safely withstand the peak inverse volta.. .f the circuit and to prevent rectifier breakdown. Since
'idual rectifier in the series-connected arrangement
or stacked units) has a maximum reverse-voltage rating, it
for the series combination of rectifiers in any
ave a total reverse-voltage rating in excess of
nverse voltage encountered in the circuit
ause a choke-input filter system is commonly
r surge, resistors are not normally used with
..is circuit. For this reason series resistors are not shown in the schematic.

NOTE: Refer to figure 17 for an understanding of output voltages as explained below.

The rectifier in each secondary leg conducts for only one-third cycle, and this results in a series of d-c output voltage pulsations. The output voltage, E_o, across the load resistance is determined by the instantaneous currents flowing through the load; therefore, the output voltage never drops to zero because of the overlapping of applied three-phase secondary voltages and the resulting rectifier conduction in each secondary leg. Because the ripple voltage is equal to three times the frequency of the a-c source, the circuit requires less filtering to smooth out the ripple and produce a steady d-c voltage than does a single-phase rectifier circuit. The peak inverse voltage across the rectifier (multiple or stacked units) in one secondary leg of the three-phase, half-wave circuit during the period of time the rectifier is nonconducting is approximately 2.45 times the rms voltage (E_{sec}) across the secondary winding of one phase. The regulation of the circuit is considered to be very good and is better than that of a single-phase rectifier circuit having equivalent power-output rating; the semiconductor rectifier characteristics of the supply. The output of the three-phase, half-wave rectifier circuit is connected to a suitable filter circuit, to smooth the pulsating direct current for use in the load circuit.

<u>Three-phase, full-wave (single "Y" secondary) rectifier</u>

Application. The three-phase, full-wave rectifier with single-wye secondary is used in electronic equipment for applications where the primary a-c source is three-phase and the d-c output power requirements are relatively high. The rectifier circuit can be arranged to furnish either a negative or a positive high-voltage output to the load.

Characteristics of three-phase, full-wave rectifier

1. Input to circuit is three-phase a-c; output is d-c with amplitude of ripple voltage less than that for a single-phase rectifier.

2. Uses six semiconductor rectifiers (multiple or stacked units).

3. Output requires very little filtering; d-c output ripple frequency is equal to six times the primary line-voltage frequency.

4. Has good regulation characteristics.

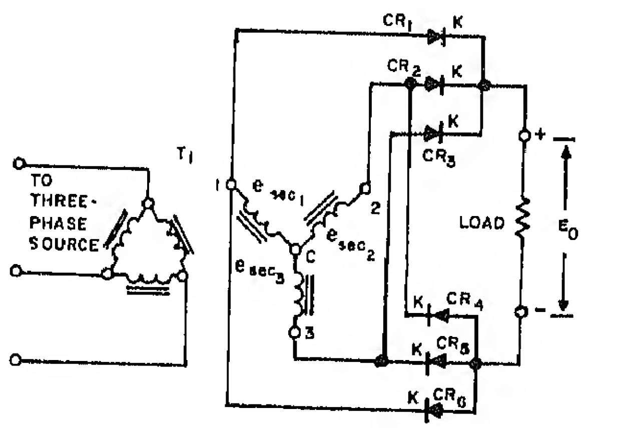
5. Circuit provides either positive- or negative-polarity output voltage.

6. Uses multiphase power transformer with wye-connected secondary windings; primary windings may be either delta- or wye-connected.

Circuit analysis

General. The three-phase, full-wave (single-wye secondary) rectifier is extensively used where a large amount of power is required by the load, such as for large shipboard or shore electronic installations. The rectifiers used in this circuit are generally forced-air cooled or oil cooled to dissipate heat. In many power-supply applications, it is desirable to provide two voltages for low-power stages. For these applications, the three-phase, full-wave rectifier circuit can be modified to supply an additional output voltage, which is equal to one-half the voltage provided by the full-wave rectifier circuit.

Circuit operation. The basic three-phase, full-wave rectifier circuit is illustrated in figure 19. The circuit uses a conventional three-phase power transformer, T_1, to step up the alternating source voltage to a high value in the wye-connected secondaries. The primary windings of T_1 are shown delta-connected, although in some instances the primary windings may be wye-connected (as for a three- or four-wire system).



Basic Three-Phase, Full-Wave (Single "Y" Secondary) Rectifier Circuit

FIGURE 19

Semiconductor rectifiers CR_1 and CR_6 are connected to secondary terminal No. 1 of transformer T_1; rectifiers CR_2 and CR_4 are connected to secondary terminal No. 2; rectifiers CR_3 and CR_5 are connected to secondary terminal No. 3. The rectifiers are identical semiconductor rectifiers. Although the schematic shows only six individual rectifiers in the circuit, each graphic diode symbol represents two or more diodes in series to obtain the necessary peak-inverse characteristics for high-voltage operation. The circuit arrangement shown in figure 19 permits either terminal of the load to be placed at ground potential, depending upon whether a positive or negative d-c output is desired; however, the circuit is commonly arranged for a positive d-c output, with the negative output terminal at ground (chassis). Also, a choke-input filter system is commonly used with this circuit; therefore, series, or surge, resistors are not normally used.

In figure 20, the voltages developed across the secondary windings of transformer T_1 are 120° out-of-phase with relation to each other and are constantly changing in polarity. At any given instant of time in the three-phase, full-wave rectifier circuit, a rectifier, the load, and a second rectifier are in series across two of the wye-connected transformer secondaries. Each of the six rectifiers conducts for 120° of an electrical cycle; however, there is an overlap of conduction periods, and the rectifiers conduct in a sequence that is determined by the phasing of the instantaneous secondary voltages. In the circuit in figure 20, two rectifiers are conducting at any instant of time, with rectifier conduction occurring in the following order: CR_1 and CR_4, CR_1 and CR_5, CR_2 and CR_5, CR_2 and CR_6, CR_3 and CR_6, CR_3 and CR_4, CR_1 and CR_4, etc. Each positive and negative peak in each of the three phases produces a current pulse in the load. Because of the nature of the rectifier conduction periods, each rectifier conducts for 120° of the cycle, and carries one-third of the total load current. The output voltage, E_o, produced across the load resistance is determined by the instantaneous currents flowing through the load; therefore, the output voltage has a pulsating waveform, which results in a ripple voltage,, because the output current and voltage are not continuous. The frequency of the ripple voltage is six times the frequency of the a-c source. Since this ripple frequency is higher than the ripple frequency of a single-phase, full-wave rectifier circuit or a three-phase, half-wave rectifier circuit, relatively little filtering is required to smooth out the ripple and produce a steady d-c voltage. The peak inverse voltage across an individual rectifier (multiple or stacked units) in the three-phase, full-wave rectifier circuit during the period of time the rectifier is nonconducting is approximately 2.45 times the rms voltage across the secondary winding of one phase. The regulation of the circuit is considered to be very good and is better than that of a single-phase rectifier or of a three-phase, half-wave rectifier circuit having equivalent power-output rating. The output of the three-phase, full-wave rectifier circuit is connected to a suitable filter circuit to smooth the pulsating direct current for use in the load circuit. A variation of the three-phase, full-wave rectifier circuit has a common terminal of the wye-connected secondaries and

rectifiers CR_4, CR_5, and CR_6 to form a three-phase, half-wave rectifier circuit. See figure 21. The circuit is fundamentally the same as that discussed earlier; therefore, the reference designations previously assigned to the basic circuit remain unchanged. One advantage of this circuit variation is that two voltages may be supplied from the same transformer and rectifier combination. One output voltage (E_{avg}) is obtained from the full-wave circuit; the other voltage ($\frac{E_{avg}}{2}$), which is equal to one-half the full-wave output voltage is obtained by using rectifiers CR_4, CR_5, and CR_6 and the common terminal of the wye-connected secondaries as a conventional three-phase, half-wave rectifier circuit. Although this circuit can supply two output voltages simultaneously to two separate loads, there is a limitation on the total current that can be safely carried by the rectifiers (CR_4, CR_5, and CR_6).

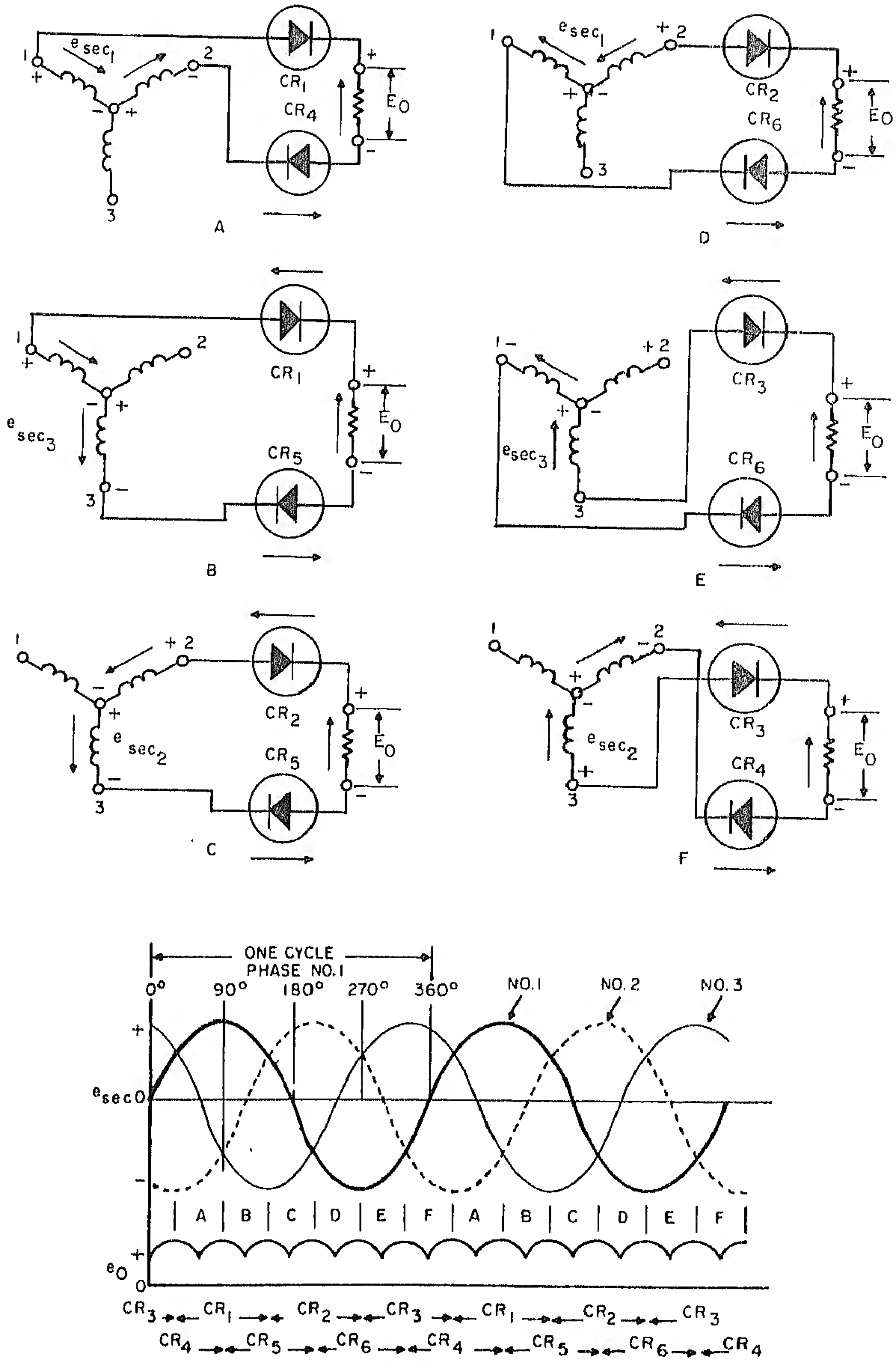
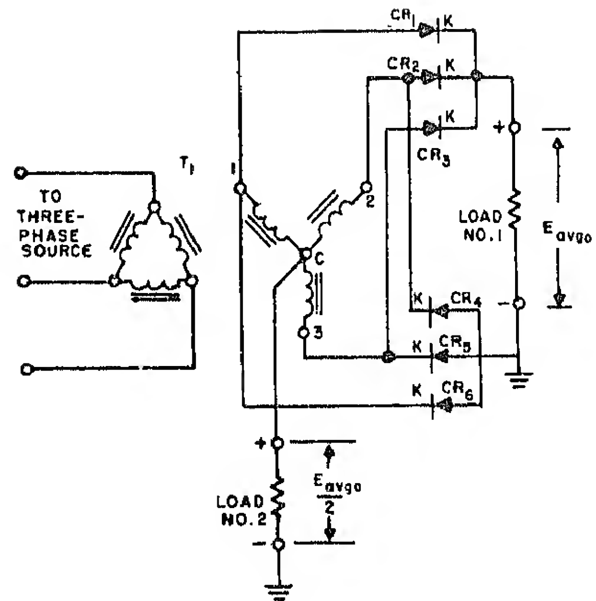

e sec1
CR1
CR4
EO
A
CR2
CR6
D
CR1
e sec3
CR5
B
CR3
CR6
E
CR2
e sec2
CR5
C
CR3
CR4
F
ONE CYCLE
PHASE NO. 1
0°
90°
180°
270°
360°
NO. 1
NO. 2
NO. 3
e sec 0
A B C D E F A B C D E F
eO
CR3 CR1 CR2 CR3 CR1 CR2 CR3
CR4 CR5 CR6 CR4 CR5 CR6 CR4

FIGURE 20



Three-Phase, Half-Wave and Three-Phase, Full-Wave Rectifier Circuit

FIGURE 21

NOTETAKING SHEET 3.1.1N

POWER SUPPLY RECTIFIERS

REFERENCES:

1. Basic Electronics, Vol. 1. NAVPERS 10087-C. Chapter 5.

2. Electronic Circuits. NAVSEA 0967-LP-000-0120. Chapter 2, pages 2-1 through 2-74.

3. Slurzberg, Morris and William Osterheld. Essentials of Radio-Electronics. Second Edition. New York: McGraw-Hill Book Company, Inc., 1961. Chapter 9.

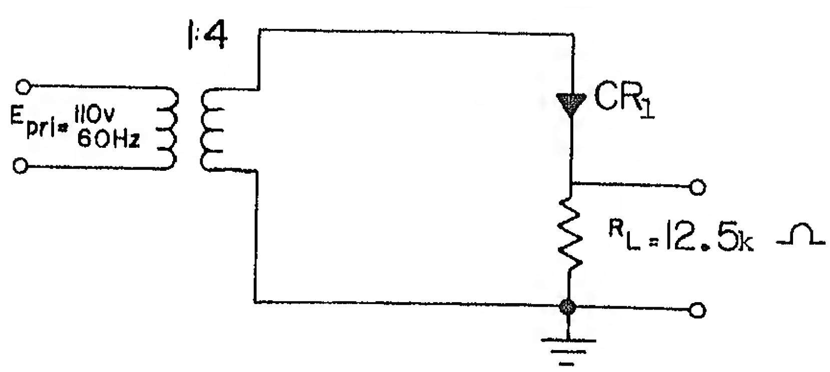
4. Slurzberg, Morris and William Osterheld. Essentials of Communication Electronics. Third Edition. McGraw-Hill Bokk Company, Inc., 1973. Chapter 6.

NOTETAKING OUTLINE:

A. Characteristics of Diodes

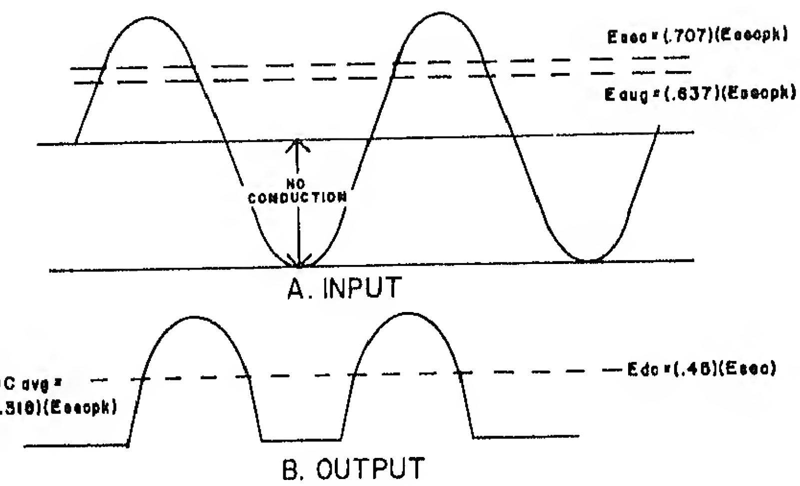
B. Half-Wave Rectifiers

1. Circuit components



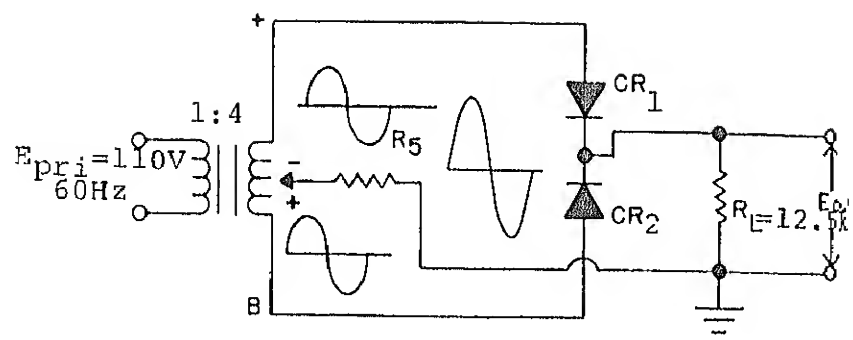
2. Circuit operation

3. Voltage relationships



4. Mathematical analysis of circuit operation

C. Full-wave Rectifiers



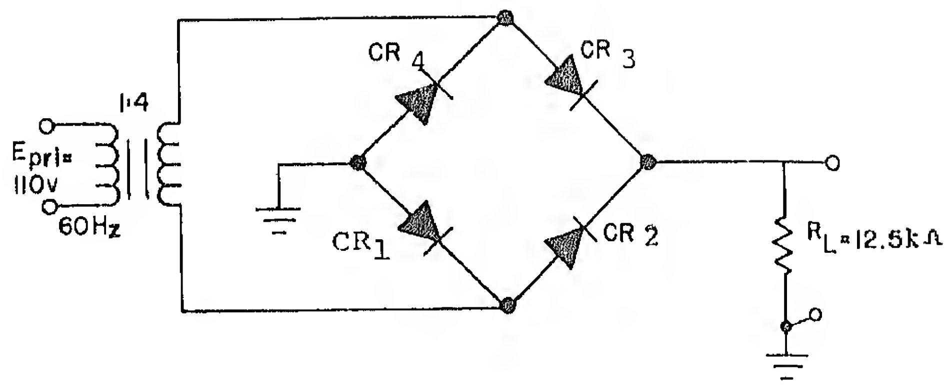
1. Circuit components

2. Circuit operation

Voltage relationships

4. Mathematical analysis of circuit operation

D. Full-Wave Bridge Rectifiers



1. Circuit components

2. Circuit operation

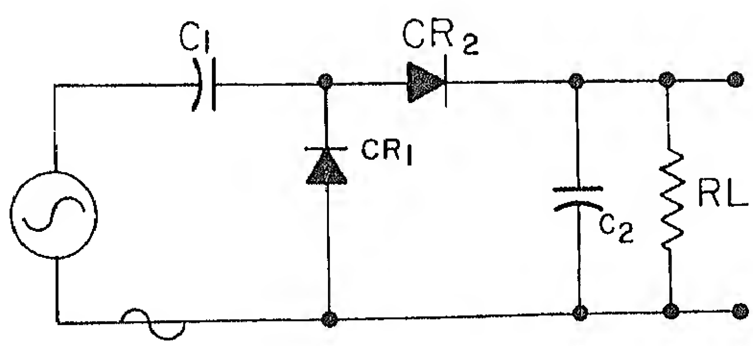
3. Voltage relationships

4. Mathematical analysis of circuit operation

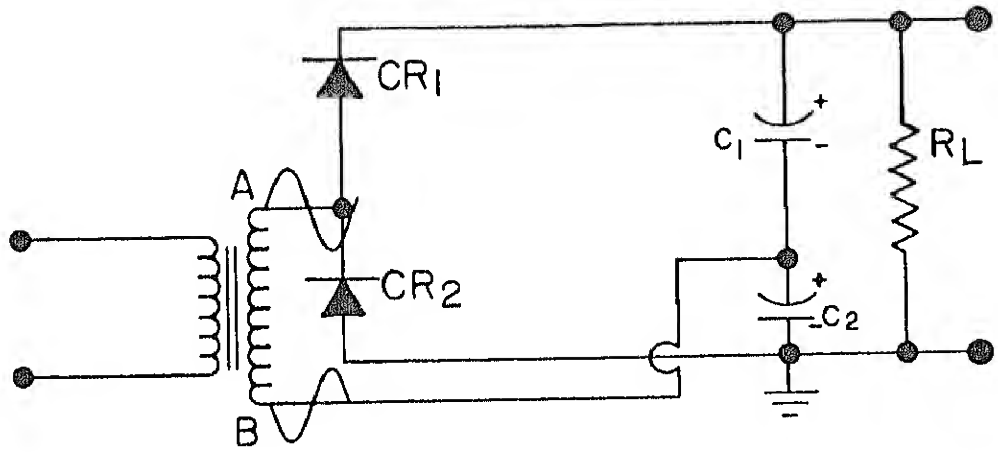
5. Circuit comparison

E. Voltage Multipliers

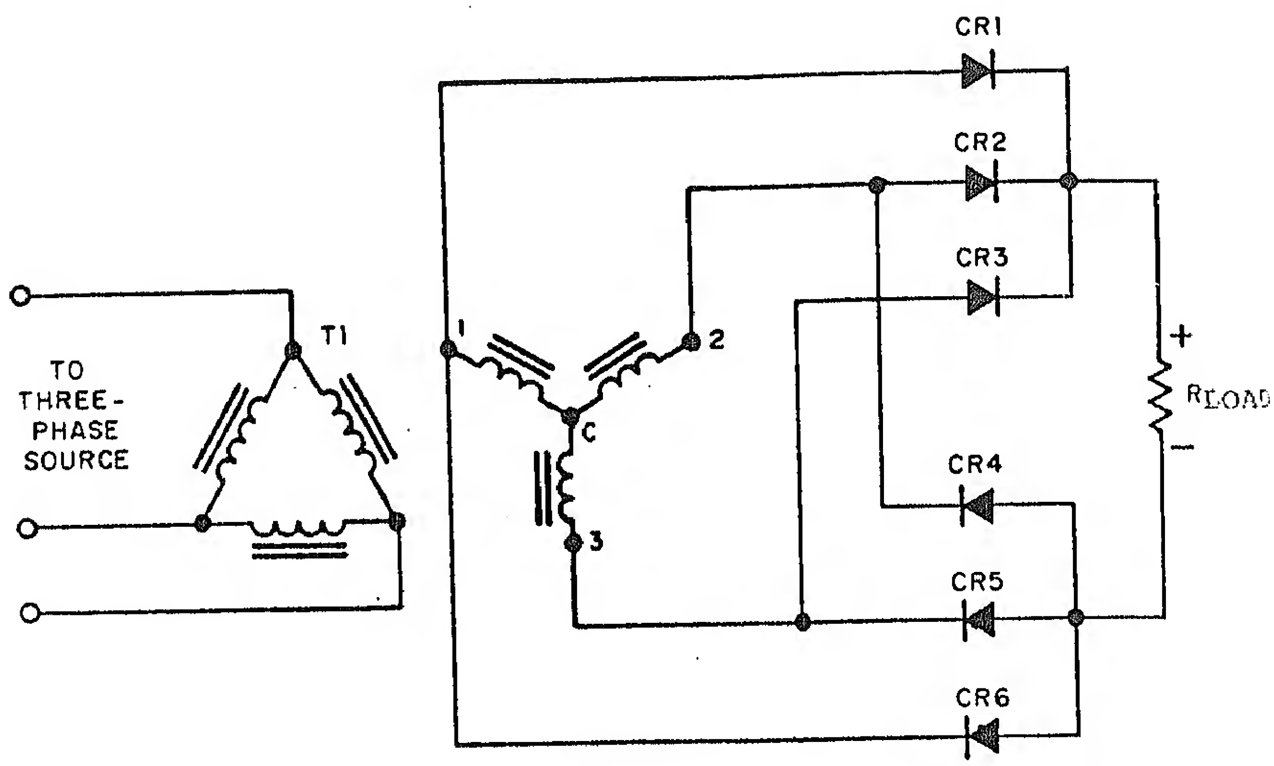
1. Half-wave voltage doubler



2. Full-wave voltage doubler



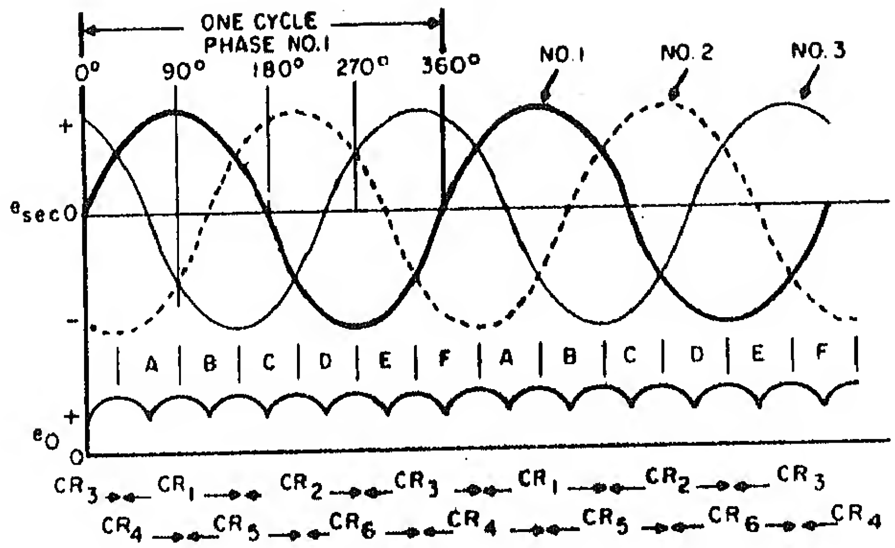
F. Three-phase, Full-wave Rectifiers



1. Circuit components

2. Circuit operation

3. Voltage relationships



INFORMATION SHEET 3.2.1I

POWER SUPPLY FILTERS

INTRODUCTION

The output of most types of rectifiers is a pulsating current. Most electronic circuits, however, require a pure direct current for proper operation. To provide this type of output, the filter circuit is used to eliminate any alternating or ripple voltage. The filter may be made up of several components, such as resistors, inductors, or capacitors, which will smooth out the d-c pulsations. This information sheet provides detailed instructions concerning the circuit operation of various types of filters used in electronic equipment. An understanding of the use of each will enhance your abilities to troubleshoot circuit malfunctions.

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INFORMATION

Shunt-capacitor filters

The shunt-capacitor filter is the simplest type of filter. As shown in figure 1(A), it consists of only a single filter element, capacitor C_1, connected across the rectifier, in parallel with the load. In order to obtain good smoothing action when using this filter, the RC time constant of the circuit should be high. Hence, both the capacitance and load resistance should be high. Better filtering results when the ripple frequency is also high. Figure 1(B) illustrates the input and output waveforms of the shunt-capacitor filter, using a medium to high value of capacitance in a full-wave rectifier circuit. Capacitor C_1 initially charges up to the peak value of the applied voltage and discharges through the load (R_L) between the rectified pulses. The charge and discharge of C_1 are indicated in (A) as is the polarity of the voltage developed across the capacitor and the load.

The chief disadvantage of the shunt-capacitor filter is poor regulation, which precludes its use in most power-supply applications. However, simplicity and effectiveness are advantages that make it preferable to more elaborate filters in some high-voltage applications. The shunt-capacitor filter is widely used in power supplies that furnish high-voltage-anode potentials to cathode-ray and similar tubes where the current drain is insignificant.

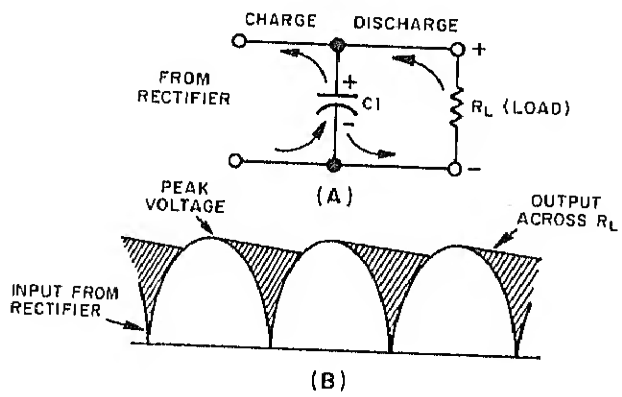

FIGURE 1.--Shunt-capacitor filter and associated waveforms.

Pi-section capacitor-input RC filters

The addition of a series resistor and a second shunt capacitor to the shunt-capacitor filter results in the basic RC capacitor-input filter shown in figure 2. Because of its resemblance to the Greek letter π (pi), it is known as a pi-section filter. The input to the filter is the output voltage from the rectifier developed across input capacitor C_1. Typical waveforms of these voltages are shown in figure 2. Both the a-c and the d-c components of the rectified current flow through series resistor R_1. Because the reactance of C_2 is small at the frequency of pulsation, most of the alternating current flows through this capacitor and is bypassed around the load resistor. The direct current flows through load resistor R_2. The charging and discharging of C_2 with the passage of the pulsating current causes a smoothing out of the ripple fluctuations, and a relatively pure direct current is delivered to the load, as is indicated by the output waveforms. The reduction in output voltage caused by the excessive voltage developed across the series-filter resistor when load current is high makes the RC filter impracticable for most applications requiring even a moderate amount of current. This type of filter is used effectively in high-voltage, low-current applications. It is also commonly used as a decoupling network in multistage amplifier circuits.

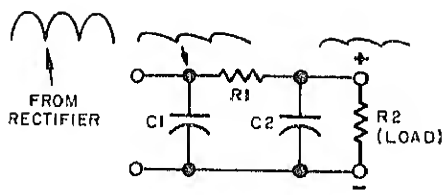

FIGURE 2.--π-section capacitor-input RC filter and associated waveforms.

Pi-section capacitor-input LC filters

The basic π-section capacitor-input LC filter has a configuration that is identical with and similar in every respect to the π-section capacitor-input RC filter with one exception--a choke coil (iron-core inductor) replaces the series resistor in the π-section network, as shown in figure 3. The π-section capacitor-input LC filter is probably used to a greater extent than any other type of filter in power-supply applications. The input to the filter section, comprising L and C_2, is the output voltage of the rectifier, developed across capacitor C_1. Typical rectifier output and capacitor C_1 input voltage waveforms are shown in figure 3. Inductor L and capacitor C_2, working together, materially reduce the alternating current remaining in the voltage across C_1 and thus supply a substantially pure d-c output voltage to the load. As in the shunt-capacitor filter, the poor regulation of the π-section capacitor-input filter is a major disadvantage. In fact, assuming equal values of C, the regulation of a power supply using a capacitor-input LC filter is actually more difficult to maintain than that of a power supply using a shunt-capacitor filter. An advantage of the capacitor-input filter is that it provides a much higher output voltage than a comparable filter of the choke-input type.

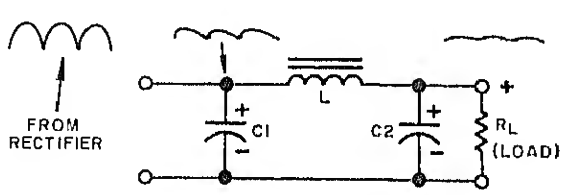

FIGURE 3.--π-section capacitor-input LC filter and associated waveforms.

L-section choke-input LC filters

With the elimination of capacitor C_1, the π-section capacitor-input filter becomes an L-section choke-input LC filter. This type of filter, along with the associated waveform, is illustrated in figure 4. Because the choke-input filter resembles the letter "L," it is often referred to as an L-section. When rectified pulses are applied to the choke coil (series inductor, L), the inductance opposes any change in current through the coil. Thus, the inductance of the coil acts to oppose any increase in current during the rapid positive excursion of the pulses, as well as any decrease in current during the equally rapid negative excursion of the pulses. This action tends to keep a constant current flowing to the load throughout the cycle, which causes the pulsating voltage (resulting from the inductance effect) developed across capacitor C_1 to remain relatively constant at a value approaching the average value of the input voltage. The low reactance presented by capacitor C_1 to the pulsating component functions to decrease the ripple amplitude in the output and thereby to increase the average d-c output voltage. One disadvantage of the choke-input filter is the significantly lower output voltage of this type of filter as compared with the higher voltage provided by a comparable capacitor-input filter. Another economic disadvantage is that, for equivalent filtering, the choke-input filter must employ higher component values than are required in the capacitor-input filter. However, the advantage of having lower peak currents in the choke-input system, which effects important savings in transistor and transformer costs, somewhat offsets the second disadvantage. Two additional advantages of using the choke-input filter, as compared with using the capacitor-input filter, are a greater power capability and easier d-c voltage regulation.

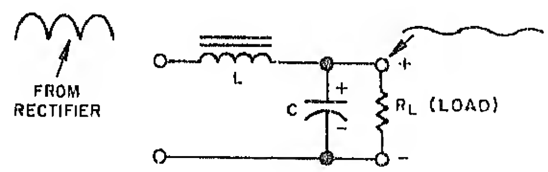

FIGURE 4.--L-section choke-input LC filter and associated waveforms.

Multiple-section filters

To enhance the filtering action further and provide a smoother rectified output voltage (beyond that possible with the simple filter circuits discussed in the preceding paragraphs), one or more

additional sections may be added to the basic filter circuit. Two multiple-section filters are illustrated in figure 5--the capacitor-input (A) and the choke-input (B). Representative waveforms indicating the approximate shape of the voltage at several different points in each type of multisection filter are also shown. Multiple-section filters are effective in those applications in which only a minimum ripple can be tolerated in the rectified output voltage to the load. If the ripple attenuation ratio of one LC section is 100 to 1, then an overall attenuation ratio of 10,000 to 1 will be obtained with two such sections; and an attenuation ratio of 1,000,000 to 1, with three LC sections. While additional filter sections will reduce the ripple in the output to a minimum, they will also result in reduced regulation. With additional sections, more resistance is placed in series with the power supply, which causes greater variations in the output voltage with variations in load current. Most multiple-section filters consist of a combination of identical LC sections; however, multiple-section filters are not restricted to this type of design. Combinations of LC and RC sections may be used effectively to satisfy filtering requirements in certain applications.

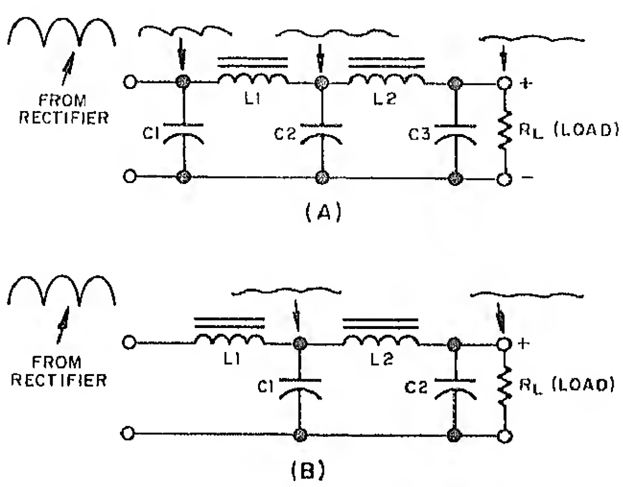

FIGURE 5.--Multiple-section capacitor-input and choke-input filters.

Resonant filters

Resonant filters are incorporated in the design of some power-supply circuits. This type of filter is usually made up of two basic circuits. One common type of resonant filter is a series-resonant (parallel-resonant) circuit in conjunction with one or more LC filter sections. Another type of filter is made up of a parallel-resonant circuit with shunt capacitors in a pi-section. (See figure 6.)

The parallel-resonant circuit consisting of L_1 and C_3 is tuned to the fundamental ripple frequency and is connected in series with the output of the rectifier. Since this type of circuit presents an extremely high impedance at resonance, the fundamental ripple frequency will be greatly attenuated in the output voltage to the load. Two serious disadvantages that limit the use of the resonant filter are as follows: (1) A change in the inductance of L_1 with a change in the load current results in detuning of the circuit and a loss in its effectiveness. (2) Harmonic frequencies "see" a much lower impedance than the fundamental ripple frequency (since the circuit is tuned to the fundamental) and are, therefore, less effectively attenuated. A conventional LC filter section is sometimes added to the resonant filter (figure 6) to offset this disadvantage.

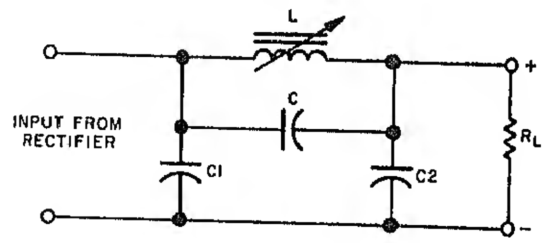

FIGURE 6.--Resonant filter.

Filter output--voltage consideration

The unfiltered output from a rectifier can be considered as a pulsating a-c voltage superimposed on a d-c voltage. The frequencies of the ripple and the amplitudes of the frequencies are the major factors that determine the amount of filtering required. Figure 7 shows four typical rectifier output waveforms. For contrast, (A) shows the smooth d-c output of a battery. The frequency of a voltage pulsation, or ripple frequency, is different for each of the rectifier output waveforms. The output of a single-phase, half-wave rectifier (B) produces pulsations at the frequency of the applied a-c voltage. If the applied a-c voltage has a frequency of 60 Hz, the ripple will also be 60 Hz. The output of a single-phase, full-wave rectifier (C) produces pulsations at twice the frequency of the applied a-c voltage, because both alternations of the input voltage are rectified. The output of a three-phase, half-wave rectifier (D) produces pulsations at three times the frequency of the applied voltage; the output of a three-phase, full-wave rectifier (E) produces pulsations at six times the frequency of the applied voltage. A comparison of the four typical output waveforms shows that each of the rectifier circuits produces a different ripple frequency for an applied a-c voltage of a given frequency and also, when the output pulses overlap (as shown D and E), an increase in ripple frequency

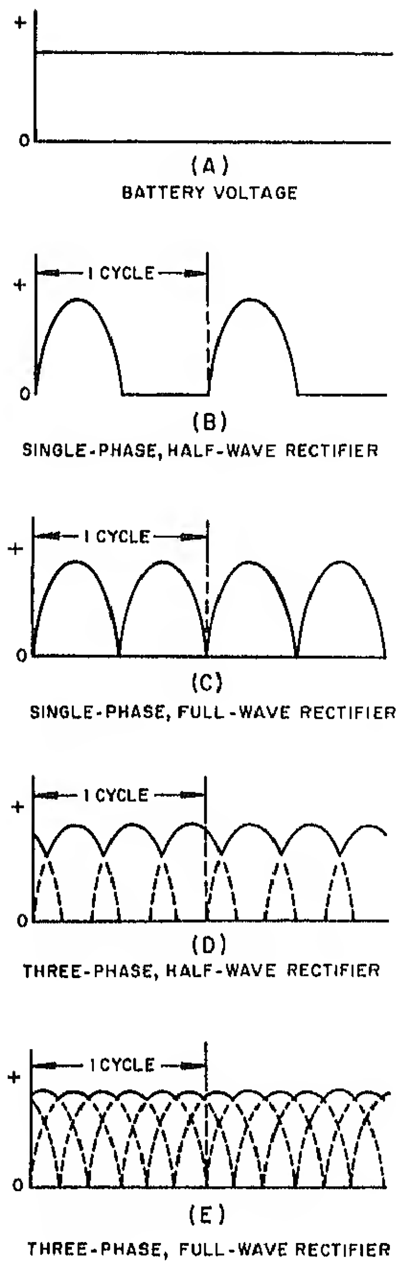

FIGURE 7.--Typical rectifier output waveforms compared with voltage output of a battery.

results in a decrease in ripple amplitude. As the ripple frequency is increased and the ripple amplitude is decreased, the rectifier output becomes easier to filter. It is desirable to furnish a voltage to the load that is free from any ripple; however, there are several practical limitations (overall regulation characteristics of the power supply; size, weight, and design of filter components; cost of components, etc.) that influence the extent of filtering possible. Furthermore, the equipment design may tolerate a small percentage of ripple without any adverse effects upon equipment performance. As a result, the filtered output from the rectifier circuit may contain a small amount of residual ripple voltage, which is applied to the load circuit.

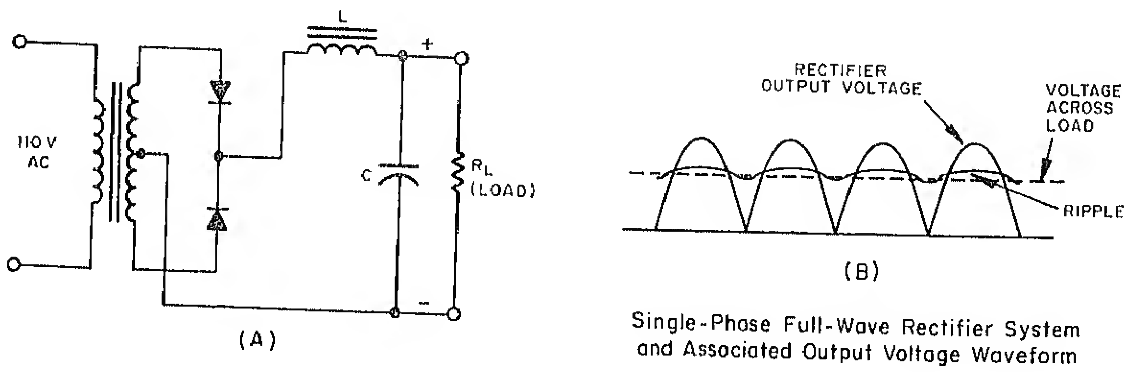

FIGURE 8.--Single-phase full-wave rectifier system and associated output voltage waveform.

Figure 8(A) shows a typical single-phase, full-wave rectifier system using a choke-input filter to provide d-c voltage to a load. The idealized curves in figure 8(B) show the shape of the output voltage from the rectifier as well as the shape of the voltage across the load. Since the output voltage of the rectifier can be considered as consisting of direct current upon which is superimposed an a-c ripple voltage, it can be shown that (by means of a Fourier analysis) the d-c component of the output wave is $2/\pi$ times the peak value of the a-c input wave. The lowest frequency component of ripple in the output is twice the input frequency and two-thirds the magnitude of the d-c component of the output voltage. The remaining ripple components are harmonics of this lowest-frequency component and rapidly diminish in amplitude as the order of harmonics is increased. In addition to the ripple frequencies present and their respective magnitudes, another very important factor that must also be considered is the amount (percentage) of residual ripple that can be tolerated by the equipment that uses the filtered voltage from the rectifier system. The effectiveness of the filter circuit in this respect is determined from the ratio of the rms value of the

ripple voltage to the average value of the output voltage at a given point. This ratio is expressed as percentage of ripple, as follows:

$$\text{Percentage of ripple} = \frac{E_{rip}}{E_{avg}} x100$$

where E_{rip} = effective (rms) value of ripple voltage
E_{avg} = average value of output voltage

As a sine wave, the effective (rms) value of ripple voltage can be expressed by the following equation:

$$E_{rip} = 0.354\ (e_{max} - e_{min})$$

OR

$$\text{Percentage of ripple} = \frac{X_C}{(X_L - X_C)}$$

where X_C = filter capacitive reactance
X_L = filter inductive reactance
C = filter capacitance in microfarads
L = filter inductance in henries

In a filter system, as the frequency of the applied voltage is increased, the reactance of a shunt capacitor decreases and the reactance of a series inductance increases. This means that the filtering effectiveness of any filter made up of shunt capacitance and series inductance is increased as the frequency of the applied voltage is increased. Thus, at the high ripple frequencies, filter components of small sizes and light weights can be used to provide the same degree of filtering as can be obtained at lower ripple frequencies with filter components of larger sizes and heavier weights.

Voltage regulation

The output voltage of a power supply decreases as the load current increases because of losses occurring at the various resistances in the rectifier and filter circuit. Figure 9 shows a graph comparing the voltage output for varying load currents from a rectifier for a simple capacitor-input filter and for a choke-input filter.

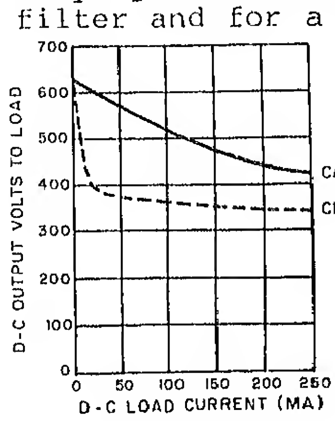

FIGURE 9.--Comparison of voltage-regulation characteristics for capacitor-input and choke-input filters.

In each, the same type of diode and transformer were used in a center-tapped full-wave circuit to supply power to an identical resistive load. It is immediately apparent, when comparing the twc curves on the graph, that while the output voltage for each value c load current was higher for the capacitor-input filter, the regulation of the power supply was far greater for the choke-input filter. Further study reveals that a change in load current in the capacitor-input filter from around 25 milliamperes to 250 milliamperes resulted in a drop in output voltage from 600 to 425 volts, or a total drop of 175 volts. For the same change in load current in the choke input, the d-c output voltage dropped from 400 volts to 350 volts, or a total of only 50 volts. Voltage regulatic is a measure of the degree to which a power supply maintains its d- output-voltage stability under varying load conditions. The amount of change in the output voltage between the no-load and the full-load condition is usually expressed in terms of the percentage of voltage regulation. The percentage of voltage regulation can be expressed as

$$\text{Percentage of voltage regulation} = \frac{(E_1 - E_2)}{E_2} \times 100$$

where $E1$ = no-load output voltage

$E2$ = full-load output voltage

An ideal power supply would have zero internal resistance (impedance) and the percentage of regulation would be zero, because there would be no difference between the no-load and the full-load output voltages. However, this is not practicable. Well designed power supplies generally have a regulation of 10 percent or less. The regulation of the choke-input filter is always more efficient than that of the capacitor-input, provided that a minimum value of load current flows through the choke at all times. Under this condition, the output voltage changes only slightly with small changes in load current. However, if the load current is reduced t approach a no-load condition, the choke cannot prevent the ---ociated filter capacitor from charging to the peak value of the ed voltage and the output votlage will rise to its maximum If the load current is normally a low value, or if the load between zero and a low value, the regulation will be d with the same circuit operating with a slightly rent. When this is true, an additional load in the or, called a bleeder resistor, is placed across the lter to improve the regulation and establish a load current for the supply. This minimum value o lows through the filter choke, improves the e power supply. The value of the current drawn by stor is usually 10 to 15 percent of the total e from the supply. The bleeder resistor takes the e divider: either a tapped resistor or a number of selected so that several values of output voltage to various loads having different voltage and ents.

Filter capacitors

A common type of capacitor used as a filter element in many receivers is the d-c electrolytic capacitor. Within the container of the electrolytic capacitor, rolled aluminum-foil plates are immersed in an electrolyte, such as an aqueous solution of boric acid and sodium borate. The actual dielectric in this type of capacitor is the thin oxide film that forms on one set of plates in the presence of a d-c polarizing voltage. The aluminum foil acts as the anode (positive terminal), and the electrolyte acts as the cathode (negative terminal) of the electrolytic capacitor. There are two general types of electrolytic capacitors--wet and dry. The physical characteristics of the electrolyte used determine the particular type of capacitor: an aqueous electrolyte in a metal container is characteristic of the wet electrolytic capacitor; a viscous or paste electrolyte in either a paper (cardboard) or a metal container forms the dry capacitor.

The most common working voltages for electrolytic capacitors (both types) range from 6 to 600 volts. Practical values of capacitance extend from 1 or 2 microfarads to as high as 2,000 microfarads, depending on the requirements of a given application. In keeping with the necessity of a wide range of working voltage and capacitance values, electrolytic capacitors are available in a variety of physical sizes. Generally speaking, the higher the voltage and the greater the capacitance, the larger the physical size. For low-voltage applications, much greater capacitance is provided in units of smaller size than in the paper-type capacitors (which provide only about one ten-thousandths as much capacitance).

Multiple-section electrolytic capacitors, which have two or more capacitor units housed in a single container, are extensively used in receiver circuits. For example, a π-section filter circuit may use a dual-section electrolytic capacitor having two 8-microfarad sections, one connected on each side of the series filter element; however, the capacitance of the different sections need not be the same. In a typical three-section capacitor, each section may have a different capacitance; or two sections may have the same value; and the third section, a different value. Any number of combinations are possible, and standardization is the exception rather than the rule.

In addition to the electrolytic capacitor, many other nonpolarized capacitors are in use; for example, paper-foil, wax-impregnated or oil-impregnated, oxide film, mica, and ceramic. For high-voltage applications, such as transmitter power supplies, the individual units are larger and have insulated-bushing terminals. The higher the voltage, the larger the unit for a given capacitance. Paper-foil capacitors are generally used at voltages from 750 to 2,500 volts. Oil-impregnated capacitors are used for voltages of 1,500 to 3,500 volts (up to 30 kilovolts for large commercial installations). Mica and ceramic capacitors are generally used as blocking capacitors or in tuned filters, since their size is usually limited to values of less than 0.25 microfarad. Small hand-portable

equipment sometimes has series-connected receiving or low-voltage electrolytic capacitors for economy (the price of two low-voltage units is considerably lower than one high-voltage unit). Since the introduction of transistors, extremely low-voltage (2-, 4-, 6-, and 12-volt) capacitors of very small physical size, with capacitance values on the order of 50, 100, and 150 microfarads or more, are in common use to supply high currents at the low voltages employed. These capacitors are used in power supplies that eliminate the necessity for, and the expense of, battery replacement.

Shunt-capacitor filter

The shunt-capacitor filter is the simplest type of filter. The application of this filter is very limited. It is sometimes used in extremely high-voltage, low-current power supplies for cathode-ray and similar electron tubes that require very little load current from the supply. Shunt-capacitor filters are also used in applications where the power-supply ripple frequency is relatively high; e.g., to filter the output of a dynamotor.

Characteristics

1. Capacitance and load-resistance values must be high (large RC time constant required).

2. Load current must be relatively small if a filter is to have good regulation.

3. Filtering efficiency increases as ripple frequency is increased.

4. Regulation of rectifier circuits is poor with the shunt-capacitor filter: voltage regulation depends mainly on value of the capacitor.

Circuit analysis

The rectifier circuits previously described provide a rectified output voltage, across the load resistance, which has a pulsating waveform. Figure 10 shows a simple shunt-capacitor filter and the waveforms obtained when the input to the filter is obtained from either a half-wave or a full-wave (single-phase) rectifier circuit. The waveforms in figure 10(A) represent the unfiltered output (without capacitor C) from the rectifier circuit when current pulses flow through the load resistance, R_L, as the rectifier conducts. Note that the dashed line representing the average value of output voltage, E_{avg}, for the half-wave rectifier indicates a value of less than the average value of output voltage, E_{avg}, for the full-wave rectifier. Both values are less than the maximum peak amplitude of the applied waveforms. With no capacitor connected across the output of the rectifier circuit, the waveform has a large value of pulsating component as compared with the average (or d-c) component. When a capacitor is connected across the output of the rectifier (across load resistor R_L), the average value of output voltage,

E_{avg}, will be increased because of the filtering action of the capacitor. In figure 10(B), a capacitor of medium value has been placed in shunt (parallel) with the load resistor, R_L. The value of the capacitor is fairly large, so that it presents a relatively low reactance to the pulsating current and stores a substantial charge. Since the rate of charge for the capacitor is limited only by the impedance of the a-c source (transformer) and the internal resistance of the rectifier (both relatively low), the RC charge time for the circuit is relatively short. As a result, when the pulsating voltage is first applied to the shunt-capacitor filter,

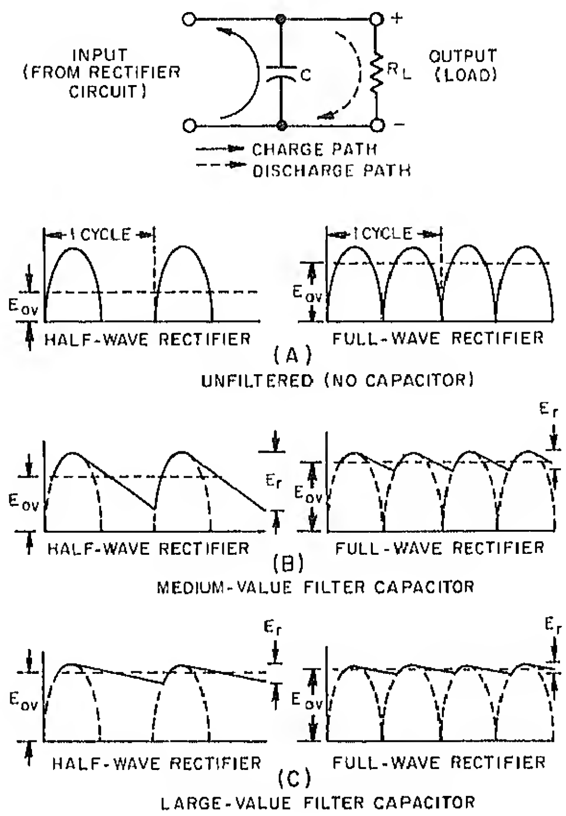

FIGURE 10.--Shunt-capacitor filter and waveforms.

the capacitor charges rapidly and almost reaches peak voltage within the first few cycles. The charge on the capacitor approximates the peak value of rectified voltage when the rectifier is conducting; and since the capacitor cannot discharge immediately, it retains its charge when the rectifier output falls to zero. The capacitor slowly discharges through the load resistance, R_L, during the time the rectifier is nonconducting. The rate of discharge for the capacitor is determined by the load resistance: if the capacitor and load-resistance values are large, the RC discharge time for the circuit is relatively long. From the waveforms shown in figure 10(B), it can be seen that the addition of capacitor C to the circuit results in an increase in the average value of output voltage, E_{avg}, and a reduction in the ripple component, E_{rip},

present across the load resistance. The capacitor partially discharges through the load, developing the output voltage until the next positive pulse occurs. When the amplitude of this pulse exceeds the value of voltage on the capacitor, the capacitor once again starts charging to the peak value. If the value of the capacitor used in the filter circuit is increased, the average value of the output voltage, E_{avg}, is also increased. Figure 10(C) illustrates the effect of increasing the value of capacitor C (over that used in figure 10(B). The time constant of the charging circuit is still relatively short, but the time constant of the discharging circuit is considerably longer. Because of the increased time constant for the discharge circuit, the large-value capacitor does not discharge as rapidly as the medium-value capacitor; therefore, the average voltage is higher and the amplitude of the ripple component, E_{rip}, is decreased. Compare the increased filtering action shown in the waveform in (C) with that in (B). Theoretically, the shunt-capacitor filter can provide any desired degree of filtering: the larger the value of capacitor C the better the filtering action, because of a lowered impedance (X_C) offered to the pulsating current and the ability of the capacitor to retain the charge longer. There is however a practical limitation to the maximum value of the capacitor used in the filter. If the peak-current rating of the rectifier is exceeded during the charging in the value of the capacitor, the rectifier will be damaged; thus, a compromise in the value of the capacitor is necessary in order to keep the maximum charging current within the peak-current rating of the rectifier.

The load resistance is also an important consideration. If the load resistance is made small, the load current increases and the average value of output voltage (Eav) decreases. The RC time constant is controlled by the value of the load resistance; therefore, the rate the capacitor discharges is a direct result of the current through the load. The greater the load current, the more rapid the discharge of the capacitor, and the lower the average value of output voltage. For this reason, the shunt-capacitor filter is seldom used with rectifier circuits that must supply a relatively large load current.

The pulsations across capacitor C and load resistance R_L, no matter how small in amplitude, are in effect a form of distortion. Although these pulsations represent a fundamental frequency, many other frequencies are also present in the output. In the majority of equipment applications, the presence of ripple voltage is not desirable; therefore, for most equipment applications, it is impracticable to use a simple shunt-capacitor filter; additional filtering (or another type of filter) is necessary to reduce the ripple amplitude to an acceptable minimum.

Consider now a complete cycle of operation, using a single-phase, half-wave rectifier operating with shunt capacitor C and load resistance R_L, shown in figure 10. Capacitor C is assumed to be large enough to ensure small reactance to the pulsating rectified current. The resistance or R_L is assumed to be much greater than the reactance of C at the input frequency.

When the circuit is energized, the rectifier conducts on the positive half of the cycle, and current flows into and charges capacitor C to approximately the peak value of the input voltage. The charge is less than the peak value of voltage by the amount of the voltage developed across the rectifier diode. The charge on C is indicated by the heavy lines on the waveforms in figures 10 (B) and (C).

On the negative half-cycle, the rectifier cannot conduct, since the anode is negative with respect to the cathode. During this interval, capacitor C discharges through load resistance R_L. The discharge of C produces the downward slope of voltage shown by the heavy lines in figures 10 (B) and (C). In contrast to the abrupt fall of the applied a-c voltage from peak value to zero (shown) in dotted lines), the voltage across C (and thus across R_L) during the discharge period decreases at a gradual rate until the time of the next half cycle of rectifier operation.

For a given value of load current, the value of C determines the rate at which the discharge voltage decreases. This rate of voltage decline and the value of C are inversely related. Thus, the rate is faster for small values of C and less for larger values of C. This indicates that for the same load current, if C (or R_L) is increased, the ripple component in the output to the load is decreased. (A long time constant filter circuit requires a longer time to charge and discharge.)

Since practical values of C and R_L ensure a more or less gradual decrease of the discharge voltage, a substantial charge remains on the capacitor at the time of the next half cycle of operation. As a result, no current can flow from the rectifier until the rising a-c input voltage on the rectifier anode exceeds the voltage of the charge remaining on C, because this charge voltage is the cathode-to-ground potential of the rectifier tube. When the anode voltage exceeds the charge voltage across C, the rectifier again conducts, and again charges C to approximately the peak value of the applied voltage. Shortly after the charge on the capacitor reaches its peak, the diode stops conducting. Because the fall of the a-c input voltage on the anode is considerably more rapid than the decrease in the capacitor voltage, the cathode quickly becomes more positive than the anode, and the rectifier ceases to conduct. During the charging period, capacitor C is connected across the output of the rectifier, and the charge time is determined by the effective series resistance, which is the diode (forward-conducting) resistance and the transformer impedance plus the resistance of the leads to the diode and capacitor. Hence, the resistance is low and C charges very quickly. During the nonconducting period, the discharge path

is through R_L, which is relatively large, so that the time constan is long. Thus, capacitor C does not discharge appreciably before the conduction cycle begins again.

The repeated charge and discharge of capacitor C (as described above) with the respective rise and fall of the input voltage constitutes the basic filtering action of this circuit. To reduce the ripple amplitude and increase the d-c component in the output voltage, capacitor C charges and stores energy when the diode is conducting and discharges to furnish current to the load when the diode is nonconducting. Using Ohm's law,

$$R = \frac{E}{I}$$

Therefore, it is evident that for the same output voltage, a heavy current drain would be caused by a lower load resistance. With a heavy load and a lower RL, capacitor C would discharge more quickl Since the output voltage represents the average charge retained on the capacitor, it can be seen that with heavy loads, the capacitor would discharge further between the periods of tube conduction. Hence, the output voltage would also be lower. This is why the single-capacitor filter is used only for very light current drains Since the output voltage for heavy loads is lower and the output ripple voltage component is also higher, the effective filtering i good only for light loads.

π-section capacitor-input RC filter

The π-section capacitor-input RC filter is limited to applications in which the load current is small. This type of filter is used i power supplies where the load current is constant and voltage regulation is not necessary, such as in the high-voltage power supply for a cathode-ray tube or as part of a decoupling network f multistage amplifiers.

Characteristics

1. Filter is composed of shunt-input capacitor, series resistor, and shunt-output capacitor.

2. Filtering efficiency increases as ripple frequency is increased.

3. Output current is much less than obtained from corresponding filter that uses a choke instead of a resistor.

4. Regulation of rectifier circuit is poor with this type of filter, requiring relatively constant load current.

5. Rectifier peak current is high with this circuit because of input capacitance.

Circuit analysis

The rectifier circuits previously described in the information sheet provide a rectified output voltage (across the load resistance) which has a pulsating waveform. Figure 11 shows a capacitor-input RC filter and the waveforms obtained from either a half-wave or a full-wave (single-phase) rectifier circuit. The waveforms shown in 11(A) represent the unfiltered output from a typical rectifier conduction. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component as compared with the d-c component.

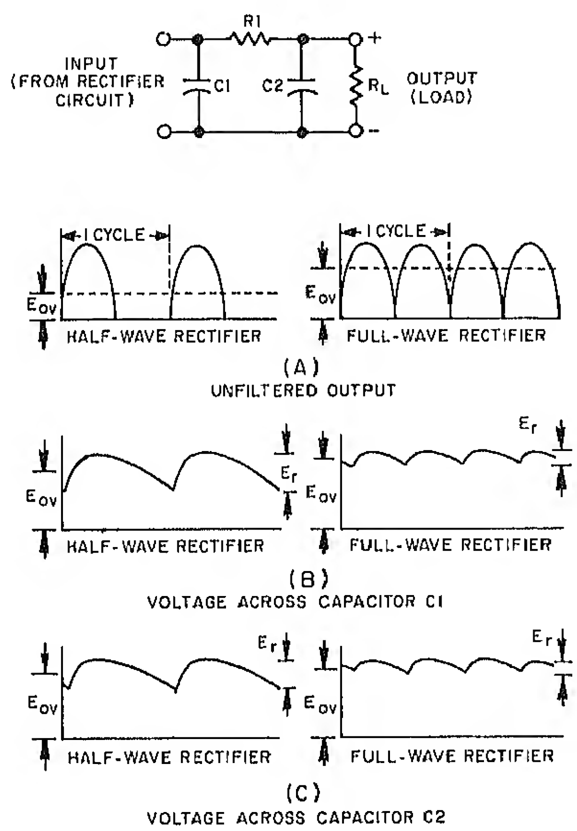

FIGURE 11.--Capacitor-input RC filter and waveforms.

The output from a pi-section RC filter ma
ripple which is considered excessive for
By adding another series filter resistor
C_3, to the basic capacitor-input filter,
the load resistance can be further atte
addition of series resistors increases
the filter, resulting in poorer regulat
voltage. For these reasons, the number
added, as well as the size of the resis
in figure 12, the added RC filter compo
inverted letter L.

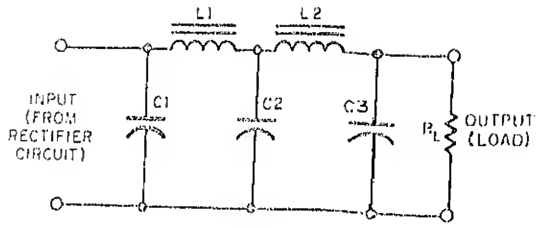

FIGURE 12.--Capacitor-input filter with RC filter section added.

π-section capacitor-input LC filter

The π-section capacitor-input filter is one of the most commonly used filters. This type of filter is used primarily in radio receivers and small audio-amplifier power supplies and in any type of power supply where the output current is low and the load current is relatively constant.

Characteristics

1. The filter is composed of shunt-input capacitor, series inductor, and shunt-output capacitor.

2. Filtering efficiency increases as ripple frequency is increased.

3. Output voltage is greater than that of choke-input filter; output current is less than that of choke-input filter.

4. Regulation of a rectifier circuit is only average with this type of filter, requiring relatively constant load current.

5. Rectifier peak current is high with this circuit because of input capacitance.

Figure 13 shows a π-section capacitor-input LC filter and the waveforms obtained from either a half-wave or a full-wave (single-phase) rectifier circuit.

The waveforms shown in (A) represent the unfiltered output from a typical rectifier circuit when current pulses flow through the load resistance each time the rectifier conducts. Note that the average value of output voltage, E_{avg} (indicated by the dashed line), for the half-wave rectifier is less than half the amplitude of the voltage peaks; the average value of output voltage, E_{avg}, for the full-wave rectifier is greater than half, but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component as compared with the average (or-d-c) component.

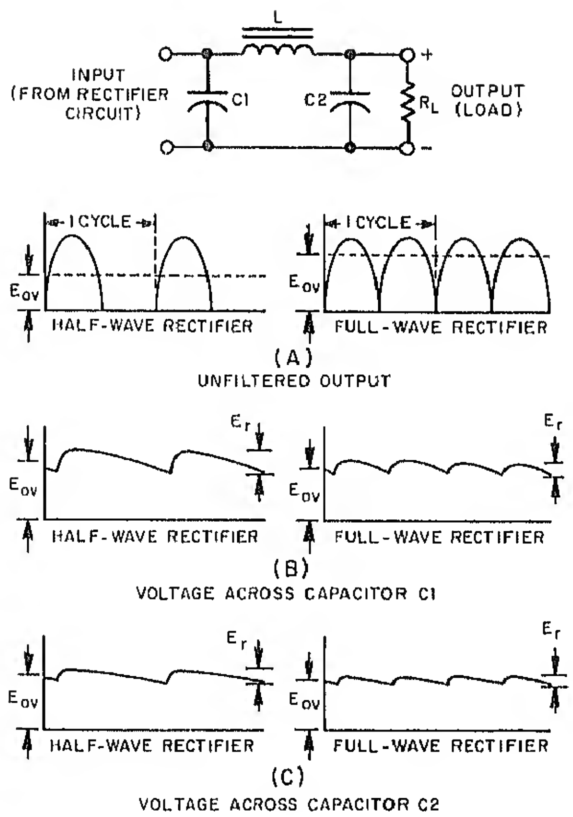

FIGURE 13.--π-section capacitor-input LC filter and waveforms.

The filter shown in the schematic of figure 13 consists of an input filter capacitor, C_1, a series inductor, L, and an output filter capacitor, C_2. It is called a capacitor-input filter, and is often referred to as a pi-section because the configuration of the schematic resembles the Greek letter π.

Capacitor C_1 is placed at the input to the filter and is in shunt with the output of the rectifier circuit. In the capacitor-input filter, the major portion of the filtering action is accomplished by the input capacitor, C_1. The average value of voltage across the input capacitor, C_1, for the half-wave and full-wave rectifier circuits is shown in figure 13(B). Note that the average value of voltage across capacitor C_1 is greater than the average value of voltage for the unfiltered output of the rectifier, shown in 13(A). The value of the input capacitor is relatively large in order to present a low reactance (X_C) to the pulsating current and to store a substantial charge. The rate of charge for the capacitor is limited only by the impedance of the a-c source (transformer) and the internal resistance of the rectifier, both of which are relatively low; therefore, the RC charge time constant for the input circuit is relatively short. As a result, when the pulsating voltage is first applied to the capacitor-input filter, capacitor C_1 charges rapidly and reaches the peak voltage within the first few cycles. The

charge on capacitor C_1 approximates the peak value of the pulsating voltage when the rectifier is conducting, but when the rectifier output falls to zero, the capacitor partially discharges through the series inductor, L, and the load resistance, R_L, during the time the rectifier is nonconducting. The larger the value of the input capacitor, C_1, the better is the filtering action; however, there is a practical limitation to the maximum value of the capacitor. If the peak-current rating of the rectifier is exceeded during the charging time for the capacitor, the rectifier will be damaged; for this reason, a compromise in the value of the capacitor is necessary in order to keep the maximum charging current within the peak-current rating of the rectifier.

The inductor (or filter choke), L_1, serves to maintain the current flow to the filter output (capacitor C_2 and load resistance R_L) at a nearly constant level during the charge and discharge periods of output capacitor C_1. The rate of discharge for capacitor C_1 is determined by the d-c resistance of the filter choke, L_1, and the load resistance, R_L, in series. The average value of voltage developed across capacitor C_2 and load resistance R_L is somewhat less than the average voltage developed across capacitor C_1. As the load current is increased, the voltage developed across inductor L increases because of the internal d-c resistance of the inductor. Also, there is a decrease in the discharge time constant for capacitor C_1 because of the greater discharge between rectifier pulses; thus, the average voltage across input capacitor C_2 is also reduced.

Series inductor L_1 and capacitor C_2 form a voltage divider across capacitor C_1. The inductor offers a high impedance and capacitor C_2 offers a low impedance to the ripple component. As a result, the ripple component, E_{rip}, appearing across the load resistance is greatly attenuated. Since the inductance of the filter choke opposes changes in the value of the current flowing through it, the average value of the voltage produced across the output capacitor, C_2, contains a much smaller value of ripple component, E_{rip}, as compared with the value of ripple produced across the input capacitor, C_1. Since inductor L_1 operates in conjunction with capacitor C_2, if either filter element is decreased in value, the other must be increased accordingly to maintain the same degree of filtering. The pulsations across capacitor C_2, which are present in spite of the action of capacitor C_1 and inductor L_1, cause C_2 to charge and discharge in the same manner as C_1. The final result is the waveform shown in part (C) of the illustration.

Some electronic equipment requires a high degree of filtering, while other equipment is not critical in this respect. The output from a single shunt-capacitor filter or from an RC or LC capacitor-input (single π-section) filter may contain an amount of ripple which is considered excessive for the equipment application. When this is true, additional filtering is necessary to attenuate the ripple component further and reduce the ripple content to a minimum. By adding another series inductor (L_1) and shunt capacitor (C_3) to the basic capacitor input filter, the ripple component across the load

resistance can be further attenuated. As shown in figure 14, the added filter components, L_2 and C_3, are called an L-section filter, because the schematic configuration resembles an inverted letter "L".

In a practical filter circuit, the reactance of the additional shunt capacitor (C_3) is much less than the reactance of the additional series inductor, L_2, and of the load resistance, R_L. Therefore, each L-section filter that is added to the basic filter reduces the output ripple amplitude more. When using a multiple-section filter,

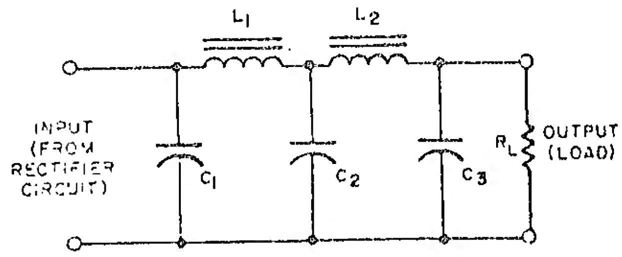

FIGURE 14.--π-section capacitor-input filter with L-section added.

the operating voltage may be taken from each separate filter section. However, when the L-section (L_2 and C_3) is added to the basic filter circuit, the regulation of the supply suffers, because adding resistance in series with the load causes greater variation of the output voltage when changes in load current occur. The voltage regulation of a power supply using a capacitor-input filter circuit is relatively poor (as compared with a choke-input filter); for this reason, the use of a capacitor-input filter is usually restricted to low-current applications, such as receivers, amplifiers, and the like, where the load current is relatively constant.

Consider now a complete cycle of operation, using a single-phase, full-wave rectifier circuit to supply the input voltage to the filter. The rectifier voltage is developed across capacitor C_1. The ripple voltage in the output of the filter is the alternating component of the input voltage reduced in amplitude by the filter action as shown in the preceding illustration.

Each time the anode of the diode becomes positive with respect to the cathode, the diode conducts and C_1 charges to the peak value of the voltage less the internal voltage developed across the diode. Conduction occurs twice during each cycle for a full-wave rectifier: with a 60Hz supply, a 120Hz ripple voltage is produced. Although each diode alternates (one conducts while the other is nonconducting and then the other conducts while the first one is nonconducting), the filter input voltage is not steady. As the positive conducting anode voltage increases (on the positive half of the cycle), capacitor C_1 charges rapidly, the charge being limited only by the transformer secondary impedance and the diode (forward-conducting) resistance. During the nonconducting interval (when the anode voltage drops below the capacitor charge voltage), C_1 discharges

charge on capacitor C_1 approximates the peak value of the pulsating voltage when the rectifier is conducting, but when the rectifier output falls to zero, the capacitor partially discharges through the series inductor, L, and the load resistance, R_L, during the time the rectifier is nonconducting. The larger the value of the input capacitor, C_1, the better is the filtering action; however, there is a practical limitation to the maximum value of the capacitor. If the peak-current rating of the rectifier is exceeded during the charging time for the capacitor, the rectifier will be damaged; for this reason, a compromise in the value of the capacitor is necessary in order to keep the maximum charging current within the peak-current rating of the rectifier.

The inductor (or filter choke), L_1, serves to maintain the current flow to the filter output (capacitor C_2 and load resistance R_L) at a nearly constant level during the charge and discharge periods of output capacitor C_1. The rate of discharge for capacitor C_1 is determined by the d-c resistance of the filter choke, L_1, and the load resistance, R_L, in series. The average value of voltage developed across capacitor C_2 and load resistance R_L is somewhat less than the average voltage developed across capacitor C_1. As the load current is increased, the voltage developed across inductor L increases because of the internal d-c resistance of the inductor. Also, there is a decrease in the discharge time constant for capacitor C_1 because of the greater discharge between rectifier pulses; thus, the average voltage across input capacitor C_2 is also reduced.

Series inductor L_1 and capacitor C_2 form a voltage divider across capacitor C_1. The inductor offers a high impedance and capacitor C_2 offers a low impedance to the ripple component. As a result, the ripple component, E_{rip}, appearing across the load resistance is greatly attenuated. Since the inductance of the filter choke opposes changes in the value of the current flowing through it, the average value of the voltage produced across the output capacitor, C_2, contains a much smaller value of ripple component, E_{rip}, as compared with the value of ripple produced across the input capacitor, C_1. Since inductor L_1 operates in conjunction with capacitor C_2, if either filter element is decreased in value, the other must be increased accordingly to maintain the same degree of filtering. The pulsations across capacitor C_2, which are present in spite of the action of capacitor C_1 and inductor L_1, cause C_2 to charge and discharge in the same manner as C_1. The final result is the waveform shown in part (C) of the illustration.

Some electronic equipment requires a high degree of filtering, while other equipment is not critical in this respect. The output from a single shunt-capacitor filter or from an RC or LC capacitor-input (single π-section) filter may contain an amount of ripple which is considered excessive for the equipment application. When this is true, additional filtering is necessary to attenuate the ripple component further and reduce the ripple content to a minimum. By adding another series inductor (L_1) and shunt capacitor (C_3) to the basic capacitor input filter, the ripple component across the load

resistance can be further attenuated. As shown in figure 14, the added filter components, L_2 and C_3, are called an L-section filter, because the schematic configuration resembles an inverted letter "L".

In a practical filter circuit, the reactance of the additional shunt capacitor (C_3) is much less than the reactance of the additional series inductor, L_2, and of the load resistance, R_L. Therefore, each L-section filter that is added to the basic filter reduces the output ripple amplitude more. When using a multiple-section filter,

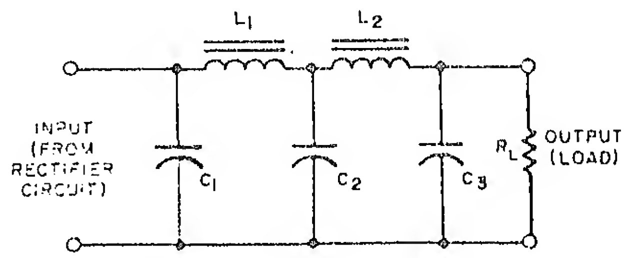

FIGURE 14.--π-section capacitor-input filter with L-section added.

the operating voltage may be taken from each separate filter section. However, when the L-section (L_2 and C_3) is added to the basic filter circuit, the regulation of the supply suffers, because adding resistance in series with the load causes greater variation of the output voltage when changes in load current occur. The voltage regulation of a power supply using a capacitor-input filter circuit is relatively poor (as compared with a choke-input filter); for this reason, the use of a capacitor-input filter is usually restricted to low-current applications, such as receivers, amplifiers, and the like, where the load current is relatively constant.

Consider now a complete cycle of operation, using a single-phase, full-wave rectifier circuit to supply the input voltage to the filter. The rectifier voltage is developed across capacitor C_1. The ripple voltage in the output of the filter is the alternating component of the input voltage reduced in amplitude by the filter action as shown in the preceding illustration.

Each time the anode of the diode becomes positive with respect to the cathode, the diode conducts and C_1 charges to the peak value of the voltage less the internal voltage developed across the diode. Conduction occurs twice during each cycle for a full-wave rectifier: with a 60Hz supply, a 120Hz ripple voltage is produced. Although each diode alternates (one conducts while the other is nonconducting and then the other conducts while the first one is nonconducting), the filter input voltage is not steady. As the positive conducting anode voltage increases (on the positive half of the cycle), capacitor C_1 charges rapidly, the charge being limited only by the transformer secondary impedance and the diode (forward-conducting) resistance. During the nonconducting interval (when the anode voltage drops below the capacitor charge voltage), C_1 discharges

through choke L_1 and load resistance R_L. The discharge path is a long-time-constant path; thus, C_1 discharges much more slowly than it charges, as indicated by the waveforms in figure 13. In this respect, the action of C_1 is similar to that of the shunt-capacitor filter described previously, with one exception. This exception is the effect of choke L_1.

Choke L_1 usually has a large value (10 to 20 henries) and offers a large inductive reactance to the 120Hz ripple component produced by the rectifier. Thus, each time C_1 starts to discharge, the inertia of the choke inductance effectively opposes a change in the ripple current through L_1. As far as the d-c component of this voltage is concerned, it is affected only by the time constant consisting of the d-c resistance of L_1 and R_1 in series with C_1.

The effect of L_1 on the charging of capacitor C_2 must now be considered. Since C_2 is connected in parallel with C_1 through choke L_1, any charge on C_1 will also tend to charge C_2. However, both the impedance and the resistance of L_1 are in series with C_2, and a voltage division of both the ripple (a-c) voltage and the d-c output voltage occurs. The greater the impedance of the choke to the ripple frequency, the less the ripple voltage appearing across C_2 and the output. The d-c output voltage is fixed mainly by the d-c resistance of the choke. For each specific value of current, there is a voltage developed across the choke; thus, the d-c voltage across C_2 is always less than that across C_1 (the higher the output current, the lower the voltage across C_2). Since C2 is supplied from C_1, which has maximum and minimum voltages produced by the charge and discharge action (the ripple voltage), C_2 also follows this charge and discharge pattern. The difference is that the C_2 action is smoothed out by the longer time constant. While the peaks and valleys exist, the values are lower. As can be seen from the waveform in figure 13(C), the overall effect is to provide a purer direct current (less ripple).

L-section LC choke-input filter

The L-section LC choke-input filter is used primarily in power supplies where voltage regulation is important and where the output current is relatively high and subject to varying load conditions. The filter is used in high-power applications, such as those found in the power-supply circuits of radar and communication transmitters.

Characteristics

1. Filter is composed of series-input inductor and shunt-output capacitor.

2. Filtering efficiency increases as ripple frequency is increased.

3. Output voltage is less than that of capacitor-input filter; output voltage from filter approaches average value of voltage from rectifier at filter input.

4. Regulation of rectifier circuits is good with this type of filter; further improvement in regulation characteristics can be realized with swinging choke-input inductor.

5. Rectifier output current approaches maximum rated current; output current is generally greater than that of capacitor-input filter.

Figure 15 shows a choke-input LC filter and the waveforms obtained from a single-phase, full-wave rectifier circuit.

The output from a single-phase, half-wave rectifier circuit is not illustrated because the choke-input filter is seldom used with this circuit. The unfiltered output obtained from three-phase, half-wave and full-wave rectifier circuits produces a higher average voltage and ripple frequency; however, the principle of filter action is essentially the same as that illustrated for the single-phase, full-wave rectifier; therefore, these waveforms are not illustrated.

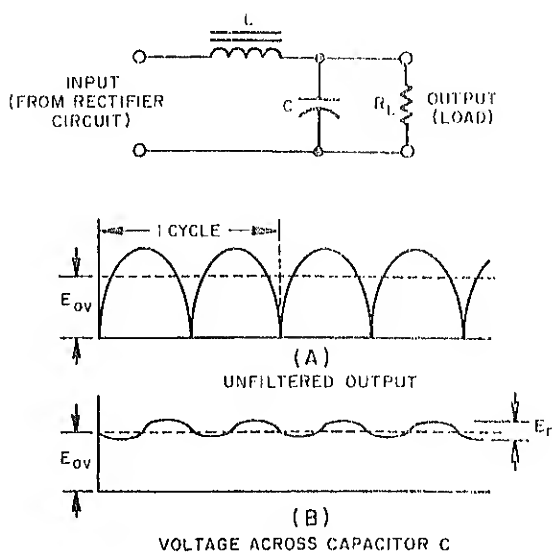

FIGURE 15.--L-section LC choke input filter and waveforms.

The waveform shown in (A) represents the unfiltered output from a typical single-phase, full-wave rectifier circuit when current pulses flow through the load resistance each time the rectifier conducts. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating current as compared with the average d-c.

The filter shown in the schematic of figure 15 consists of an input inductor or filter choke, L_1, and an output filter capacitor, C_1. The filter illustrated, called a choke-input filter, is often referred to as an "L-section filter" because the schematic configuration resembles an inverted letter L.

Inductor L_1 is placed at the input to the filter and is in series with the output of the rectifier circuit. Since the action of an inductor is to oppose any change in current flow, the inductor tends to keep a constant current flowing to the load throughout the complete cycle of the applied voltage. As a result, the output voltage never reaches the peak value of the applied voltage; instead, the output voltage approximates the average value of the input to the filter. Also, the reactance of the inductor (X_L) reduces the amplitude of ripple voltage without reducing the d-c output voltage an appreciable amount.

The shunt capacitor, C_1, charges and discharges at the ripple frequency, but the amplitude of the ripple voltage, E_{rip}, is relatively small, because the inductor, L_1, tends to keep a constant current flowing from the rectifier circuit to the load. The reactance of the shunt capacitor (X_C) presents a low impedance to the ripple component existing at the output of the filter, and the capacitor attempts to hold the output voltage relatively constant at the average value of the voltage. Since the reactance of the series inductor (X_L) is greater than the reactance of the shunt capacitor (X_C) and the reactance of the shunt capacitor (X_C) is less than the load resistance, R_L, the amplitude of the ripple frequency at the output of the filter is considerably reduced from that present at the input to the filter circuit. The output waveform is shown in figure 15(B). Assuming a single-phase, full-wave rectifier circuit, note that the frequency of the ripple voltage E_{rip}, is twice the frequency of the applied voltage.

Both the output voltage from the filter and the peak current of the rectifier depend upon the inductance of the choke and the resistance of the load. The minimum value of inductance necessary to keep the output voltage from increasing above the average value of rectified a-c is called the critical value of inductance. If the inductance of the input filter choke is less than the critical value for the circuit, the filter acts more like a capacitor-input filter, and the output voltage will rise above the average value.

The critical value of inductance is given by the expression

$$L_h = \frac{E_{out}}{I_{out}}$$

where:

L_h = critical inductance in henries

E_{out} = output of power supply in volts

I_{out} = current drawn from power supply in milliamperes

An increase in the value of choke inductance above the critical value will decrease the ratio of peak-to-average rectifier current and maintain a more uniform current flow through the inductor. Increasing the value of inductance above a certain value, called the optimum value of inductance, does not provide any appreciable improvement in performance or filtering efficiency. In practice, the optimum value of inductance for a given set of conditions is considered to be twice the critical value of inductance.

The value of inductance required for the filter varies directly with the effective load resistance, R_L. Since the inductance of a filter choke varies inversely with the d-c flowing through it, an increase in the load resistance causes the ratio of peak-to-average current to decrease; conversely, a decrease in the load resistance causes the ratio of peak-to-average current to increase.

The regulation of a power supply using a choke-input filter can be improved by the use of a swinging choke as the input inductor. A swinging choke is a choke whose inductance varies inversely with respect to the current flowing through it over the specified operating range. It is designed to have slightly more than the critical value of inductance at full load and an optimum value of inductance at no load. This characteristic maintains the peak-to-average current ratio within certain limits over a considerable range of changing load currents and results in improved regulation for the supply.

The choke-input filter is widely used in electronic equipment where the power supply is required to deliver relatively high values of current to the load with good regulation characteristics. Some equipment requires a high degree of filtering, while other equipment is not critical in this respect. The output from a single choke-input filter may contain an amount of ripple that is considered excessive for the equipment application. It then is necessary to use additional filtering to attenuate further the ripple component. By adding another series inductor, L_2, and a shunt capacitor, C_2, to the basic choke-input filter, the ripple component across the load resistance can be further attenuated. As shown in figure 16, with the addition of filter components, L_2 and C_2, the schematic configuration resembles an inverted letter "L".

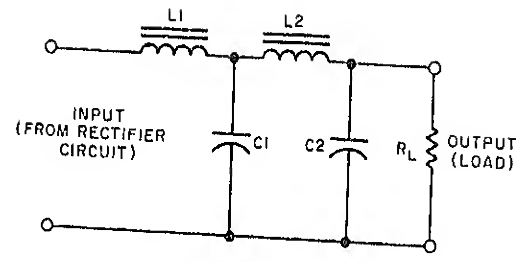

FIGURE 16.--Choke-input filter with L-section added.

In a practical filter circuit, the value of reactance in the shunt capacitor (C_2) is much less than the reactance in the series inductor (L_2) and the load resistance, R_L. Therefore, each L-section filter added to the basic filter further reduces the output ripple amplitude. However, when an L-section (L_2 and C_2) is added to a basic filter circuit, the regulation of the supply suffers somewhat, because the added resistance of the inductor (L_2) is in series with the load and causes a variation of the output voltage when changes in load current occur. Although the voltage regulation of a power supply using a choke-input filter circuit is good (as compared with one using a capacitor-input filter), the regulation can be further improved if inductor L_1 is a swinging choke. In fact, the circuit may be designed to overregulate, so that the rise in average voltage across capacitor C_1 compensates for the additional voltage drop occurring across inductor L_2. As a result, the output voltage tends to remain constant.

The inductance of any iron-core inductor shows a marked decrease as magnetic saturation is reached. The core of ordinary inductors is designed so that saturation occurs at a value just above the maximum current rating. Swinging chokes are generally designed to have one or more air gaps in the laminated core. Figure 17 illustrates a swinging choke that has two air gaps--one large and one small. (The sizes of the gaps are exaggerated in the illustration.)

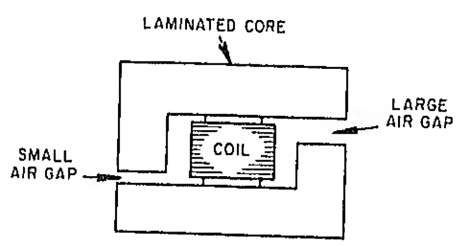

FIGURE 17.--Swinging choke with to air gaps.

The purpose of the large gap is to provide effective inductance at the largest currents, while that of the small gap is to assure high inductance at the smallest currents. Saturation of the core starts at some specified current; at full rated current, saturation is almost complete. Swinging chokes are rated to indicate the variations of inductance with variations of current through the coil. A rating of 15 to 3 henries at 25 to 250 milliamperes, for example, means that the value of inductance is 15 henries at 25 milliamperes, and reduces to only 3 henries at 250 milliamperes. When handling small currents, the swinging choke functions as a conventional choke-input filter. For larger currents, where the output voltage tends to drop, the inductance decreases and the filter starts to approach the characteristics of a capacitor-input filter. Because the decrease in inductance permits the capacitor to charge more nearly to the peak value instead of the average value, the loss of voltage in the d-c resistance of choke L_2 is thereby compensated for, and the output voltage tends to remain constant. As a result, regulation is greatly improved.

The output voltage available from a power source using a choke-input filter circuit is much less than that obtained with a capacitor-input filter. However, since the input choke opposes a rapid buildup of current, no abrupt peak-rectifier currents occur with the choke-input filter as with the capacitor-input filter. Therefore, the rectifier can deliver a higher continuous current to the load without exceeding its maximum safe ratings.

Detailed circuit operation.

Consider now one cycle of operation of the basic choke-input filter, as illustrated in figure 15 with waveforms:

The input to the filter circuit is the output of the single-phase, full-wave rectifier. The rectified pulses applied to the filter are as shown in figure 15(A). During the rising portion of the input voltage, choke L_1 produces a back electromotive force which opposes the constantly increasing input voltage. The net result is to prevent the rapid charging of the filter capacitor C_1. Thus, instead of reaching the peak value of the input voltage, capacitor C_1 is charged only to the average value of input voltage. After the input voltage reaches its peak and decreases, the back electromotive force tends to keep the current flowing in the same direction, in effect broadening the peak.

During the rising portion of the pulse, the current flow through L_1 is reduced; and during the falling portion of the pulse, the current continues to rise until the diminishing energy of the pulse as it approaches zero becomes insufficient to maintain the current, which then commences to decrease.

When the next pulse starts, the back electromotive force is still opposing an increase in current, and the current continues to decrease. (The choke, in effect, shifts the ripple peaks almost 90° while current through L_1 starts to rise. This cycle of operation is continually repeated during the time the circuit is energized and rectified pulses are applied to choke L_1. The fluctuating voltage that results from the action of choke L_1 appears across capacitor C and load resistor R_L in parallel. The low reactance of the capacitor to this ripple voltage effectively bypasses the ripple voltage so that the amplitude of the ripple voltage in the filter output is significantly reduced.

The voltage across C_1 is the d-c component or output voltage, and is produced by the charging C_1 through L_1. Essentially, the charging of C_1 is controlled by the value of the time constant, consisting of the d-c choke resistance in series with C_1. Such a typical time constant is comparable to a tenth of a second, rather than a microsecond or a millisecond. Thus, it takes many cycles of operation to charge C_1. The discharging of C_1 through the load is usually slower than the charge time, since the load resistance is normally greater than that of the choke. Therefore, the output voltage tends to remain fairly constant. The choke-input filter is effective in reducing the ripple voltage because choke L_1 and capacitor C_1 act as an a-c voltage divider for ripple voltage. With the impedance of L_1 high and the impedance of C_1 low, any ripple voltage appearing across C_1 is small, because of the large voltage drop across L_1, and is effectively bypassed around the load by the low value of X_C.

NOTETAKING SHEET 3.2.1N

POWER SUPPLY FILTERS

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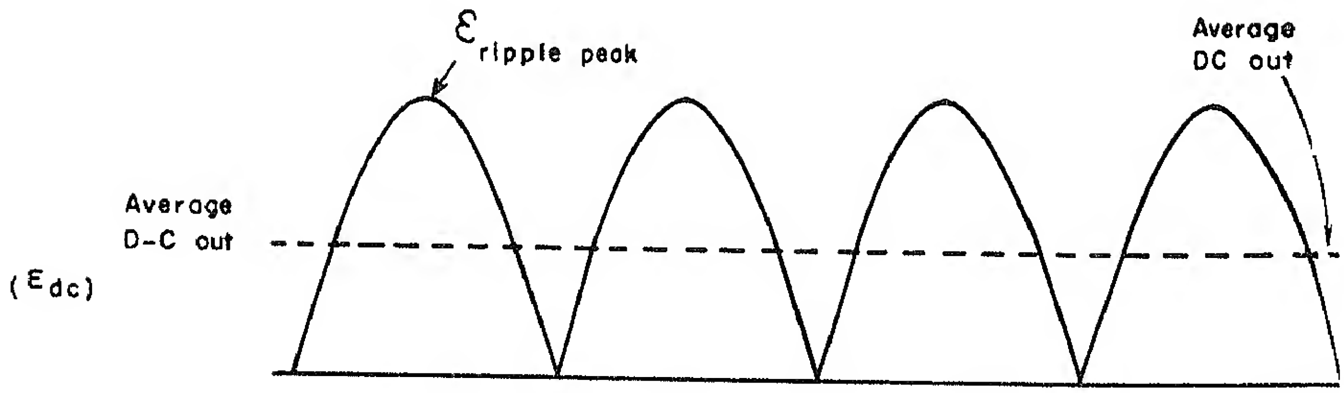
NOTETAKING OUTLINE:

A. General Information

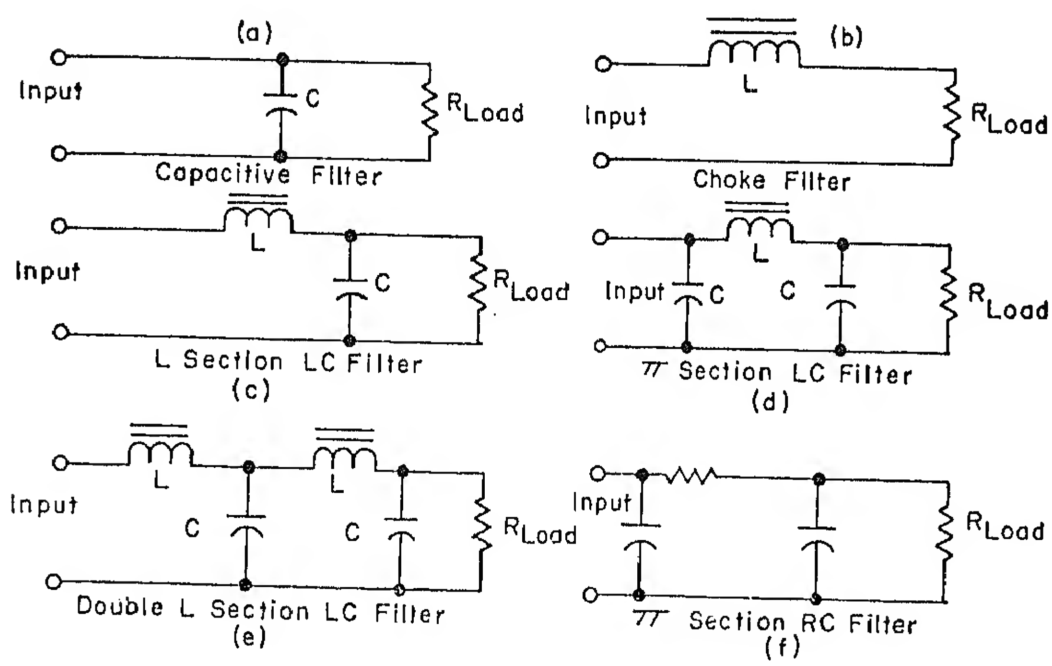
1. Ripple voltage components

2. Purpose of a filter

3. Voltage regulation

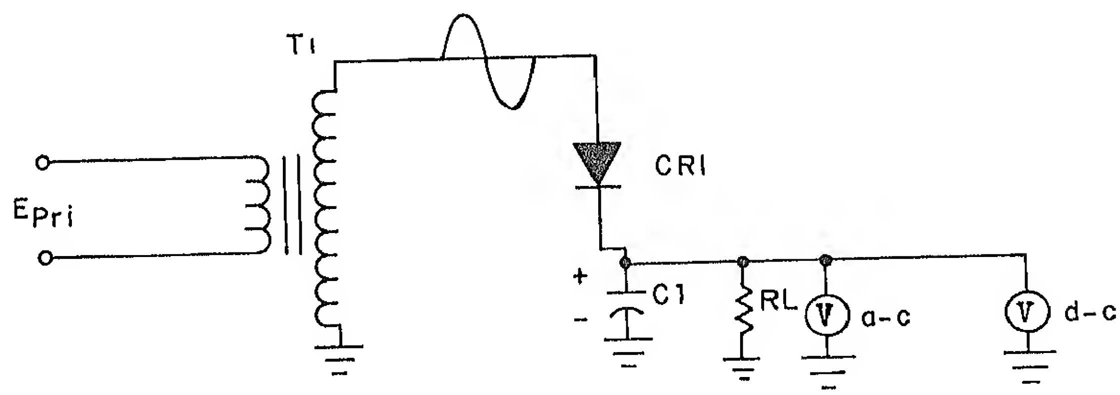


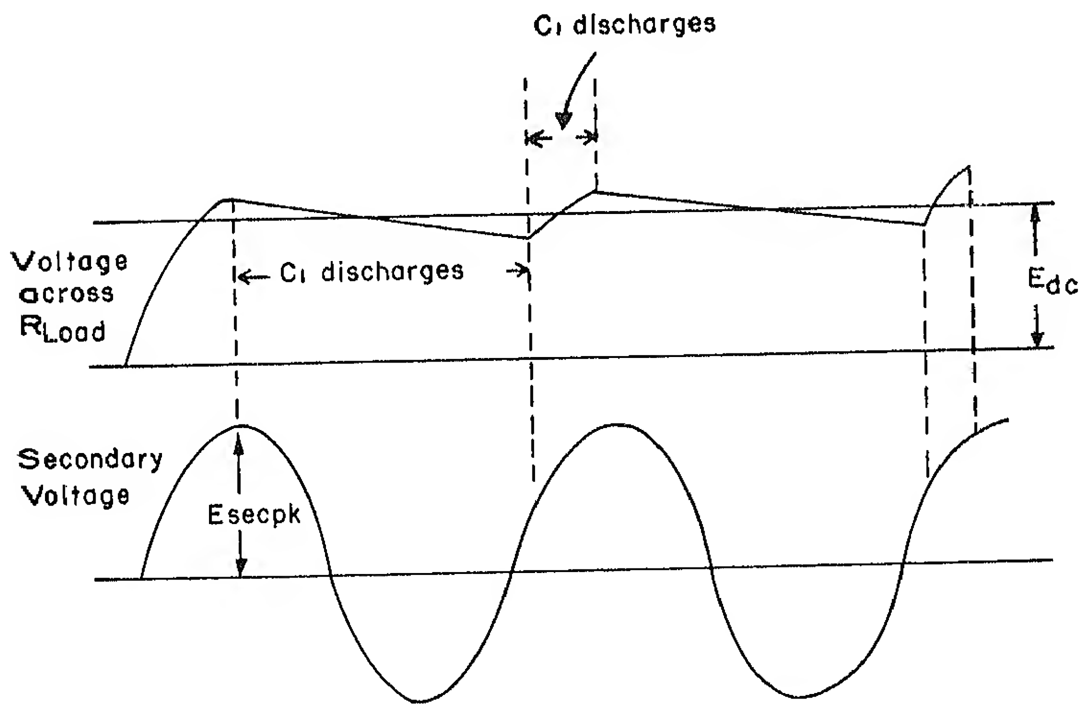
4. Types of filter sections



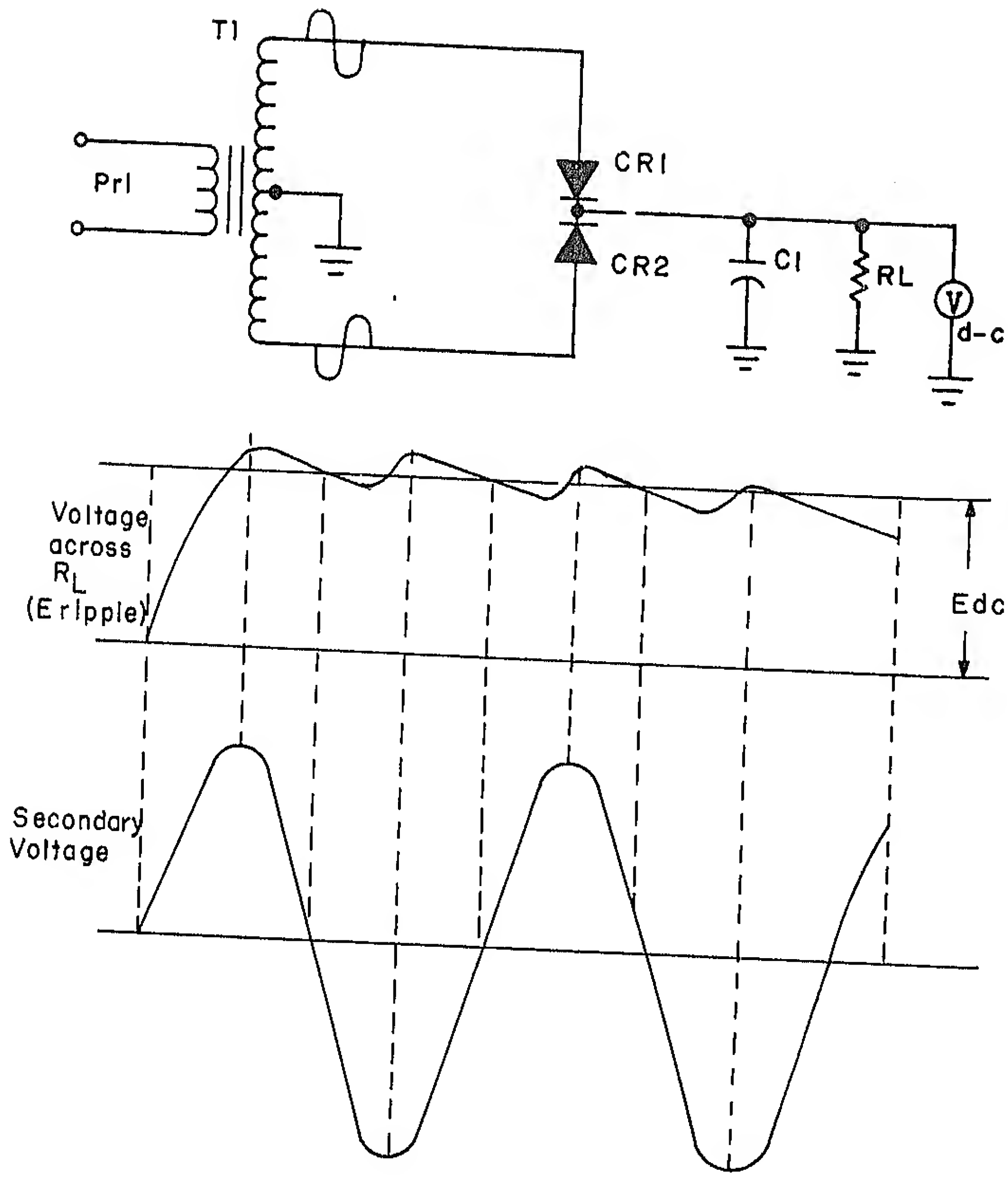
Capacitor-input Filters

1. Half-wave rectifier with capacitor-input filter



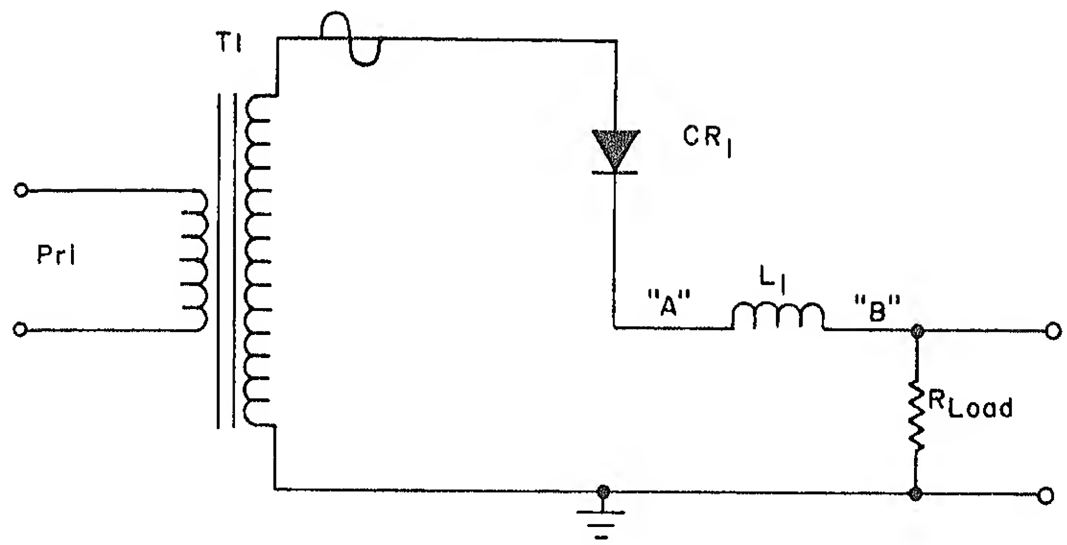


2. Full-wave rectifier with capacitor-input filter

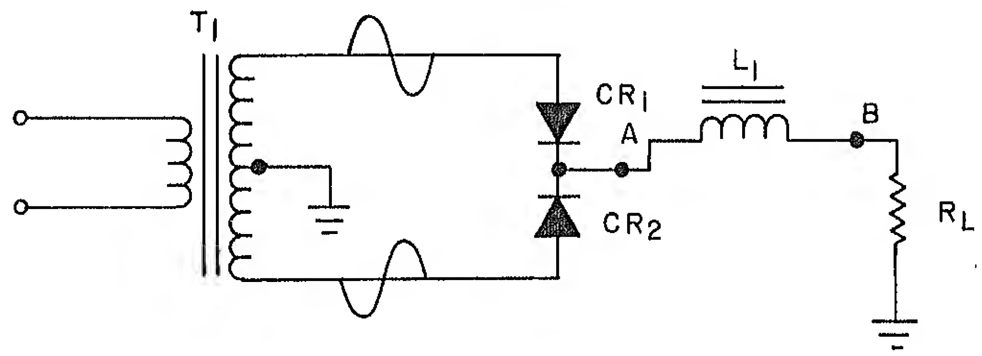


C. Inductive-input Filters

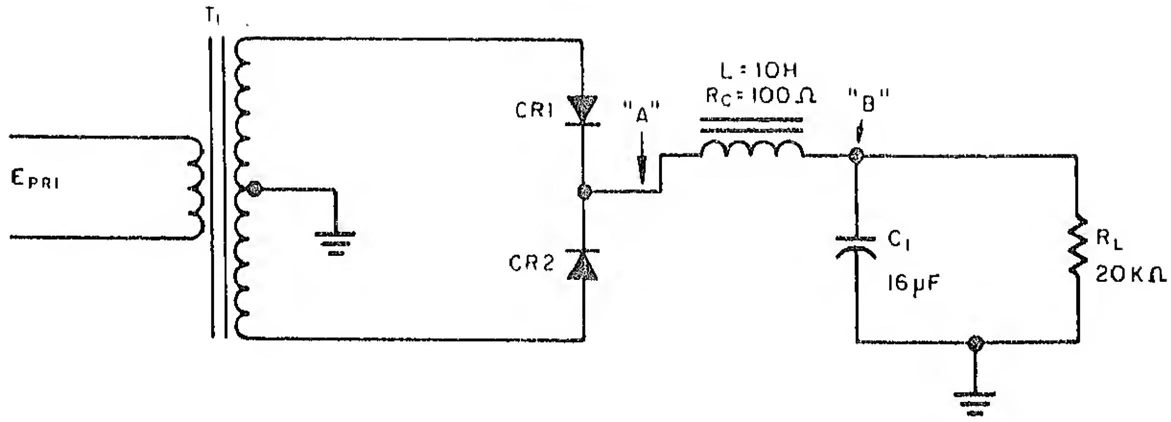
1. Half-wave rectifier with inductor-input filter



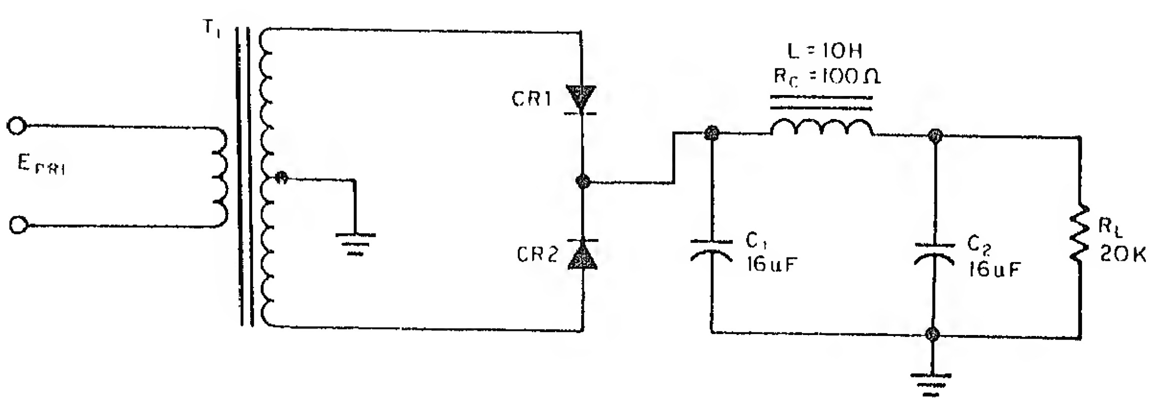
2. Full-wave rectifier with inductor-input filter



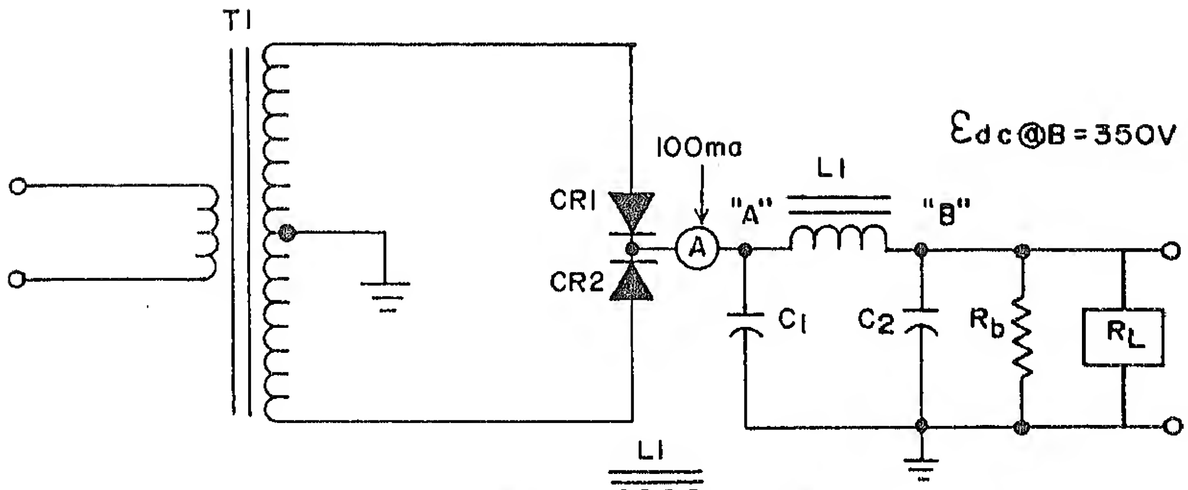
D. L-section, LC Choke-input Filters (full-wave rectifier)

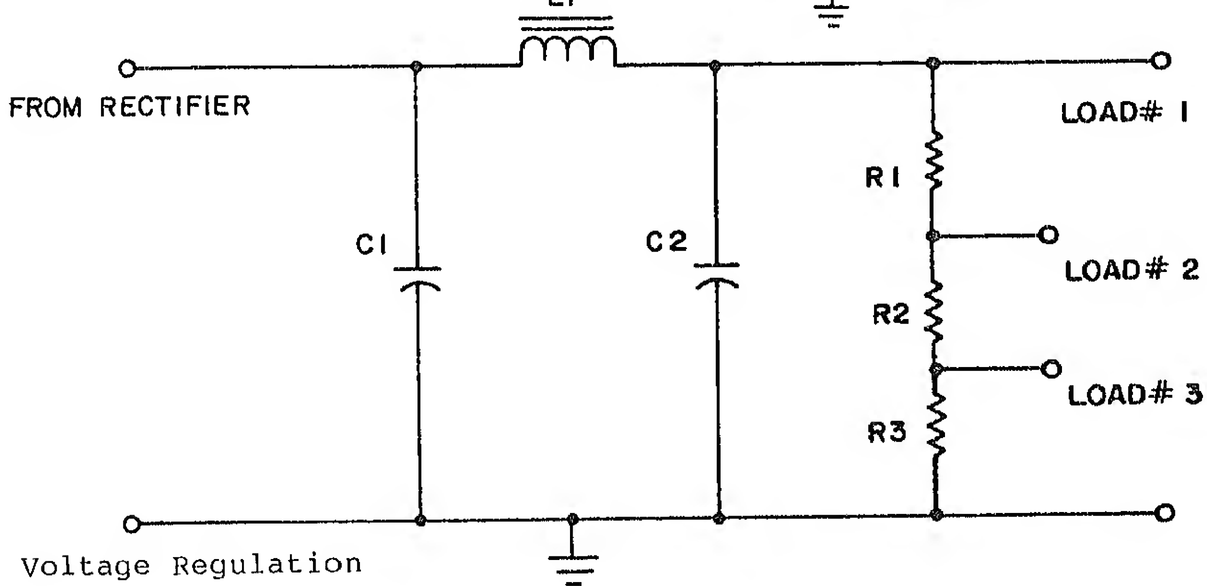


E. -section, LC Capacitor-input Filters (full-wave rectifier)



F. Bleeder Resistor





G. Voltage Regulation

INFORMATION SHEET 3.3.1I

POWER SUPPLY REGULATORS

INTRODUCTION

Variations in the voltage of the a-c input to the power supply will cause the output voltage to vary. In addition, various load circuit conditions will also cause variations in the output voltage. There are a number of power supply applications where the voltage applied to the load must be maintained practically constant. A well designed power supply regulator reacts automatically to compensate for changes in the voltage supplied to a load.

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2. Basic Electronics, Vol. I. NAVPERS 10087-C. Chapter 8, pages 173 top 178.

3. Slurzberg, Morris and William Osterheld. Essentials of Communication Electronics, Third Edition, McGraw-Hill, Inc., 1961.

Basic types

Although a variety of circuit arrangements are possible for power supply voltage regulators, they are generally of two basic types--the shunt and the series. The shunt is commonly used where input voltage variations are small and the load remains relatively constant. Most applications require the series regulator. The series is a more efficient regulator and is used in power supply applications where the load resistance and input voltage are large. Variations of the basic series semiconductor regulator include the constant-current regulator and the switching regulator. Where a constant current rather than a constant voltage is the primary requirement, the series current regulator is employed. Typical switching regulators include the silicon-controlled rectifier, the transistor-phased rectifer, and the transistor chopper.

When good stability is required and the input voltage and load current are subject to excessive variation, a regulator-amplifier circuit is employed in the shunt and series regulators. Essentially, the regulator-amplifier circuit in semiconductor regulators is a high-gain, direct-coupled amplifier having low noise and good stability characteristics. In direct-coupled amplifiers using semiconductors, drift caused by temperature changes during operation is always a design problem; therefore, a regulator-amplifier circuit using semiconductors is always a more complex circuit than is its electron-tube equivalent. Moreover, the voltage stability of the semiconductor reference-voltage circuit with respect to temperature

changes is another important design consideration. As a result of these and other design problems, it is necessary to provide temperature compensation at critical points throughout the circuit in order to obtain the best possible overall performance characteristics for the semiconductor regulator circuit.

Shunt regulator. The shunt regulator, while one of the simplest semiconductor regulators, is usually the least efficient. It may be used to provide a regulated output where the load is relatively constant, the voltage low to medium, and the output current high. The shunt regulator utilizes the voltage-divider principle to obtain regulation of the output voltage.

Figure 1 shows the shunt regulator reduced to its fundamental form. The fixed resistor R_S is in series with the parallel combination of the load resistor, R_L, and the variable resistor, $R_{regulated}$, and forms a voltage divider across the input circuit.

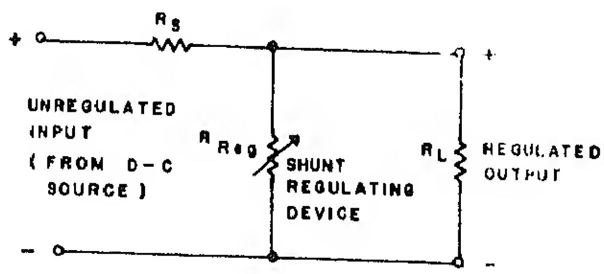


FIGURE 1-Simple shunt-type voltage-regulator circuit.

A brief operational description of the basic shunt regulator will serve to explain the manner in which regulation of the output voltage is achieved.

All current that flows in the complete circuit passes through the series resistor, R_S. The magnitude of this current and thus the value of the voltage drop across R_S are controlled by variable resistance R_{reg}. The voltage across R_S is equal to the difference between the larger voltage of the d-c source and the output voltage across load resistance R_L. The difference voltage across R_S is varied by action of resistance R_{reg}, as required, to compensate for circuit changes and maintain the output voltage to the load constant at the desired value.

If the input voltage to the regulator circuit decreases, the voltage across load resistor, R_L, and the variable resistance, R_{reg}, tends to decrease. To counteract this decrease, the resistance of R_{reg} is increased, which reduces the total current flow through R_S and thereby the voltage drop across it. Thus, by decreasing the difference voltage of R_S to compensate for the decrease in the

input voltage, the output voltage remains constant at its nominal value. Conversely, if the input voltage increases, the voltage across R_L and R_{reg} tends to increase. To counteract the increase, the resistance of R_{reg} is decreased. This results in more current through R_S and thus an increase in the voltage developed across it. The increase in the difference voltage compensates for the increase in the input voltage, and again, the output voltage remains constant at the regulated value.

The shunt regulator must be capable of withstanding the entire output voltage of the d-c source; however, it does not have to carry the full load current unless it is required to regulate from the no-load to the full-load condition. Since series-dropping resistor R_S, used with the shunt regulator, has relatively high power dissipation, the overall efficiency of this type of regulator may be less than that of other types. One advantage of the shunt regulator is the inherent overload and short-circuit protection offered. The series resistor, R_S, is between the d-c source and the load; and thus, a short circuit or overload merely decreases the output voltage from the regulator circuit. Note that under no-load conditions, however, the shunt regulating device must dissipate the full output; therefore, the shunt regulator is most often used in constant-load applications.

From the general discussion given in the preceding paragraphs, it can be seen that the shunt voltage regulator is essentially a voltage-divider circuit, with the output voltage across the load being held essentially constant, regardless of input voltage or load current variations. The control action required to vary the resistance of R_{reg} and, consequently, to develop a variable-voltage drop, is completely automatic. This basic principle of voltage regulation is used in the transistorized, shunt-type voltage regulators to be described later in this section of the information sheet.

Series regulator. The series regulator, as the name implies, places the regulating device in series with the load; regulation occurs as the result of varying the voltage developed across the series device. The series regulator is preferable for high-voltage and medium-output-current applications where the load may be subject to considerable variation. Most critical semiconductor applications require that a regulated voltage source utilizes the series regulator; and as a result, there are many regulator circuit configurations. These circuit configurations vary from one application to another, depending upon the regulation required to be maintained over a given temperature range. The series regulator employs a regulator-amplifier circuit which has the same basic function as the regulator-amplifier circuit in the electron-tube regulator.

The series regulator can be compared with a variable resistor in series with the d-c source and the load, thus forming a voltage divider. The variable-resistance action of the series regulating device maintains the output voltage across the load resistance at a constant value.

A simple series voltage-regulator circuit is shown in figure 2 to he explain this principle of voltage regulation. The variable resistor R_S, is in series with the load resistance, R_L; thus, the two resistances in series form a voltage divider across the input voltage. Th load current passes through R_S and develops a voltage across it. Th voltage developed across R_S depends upon the value of resistance of and the load current through it. Since the input voltage to the regulator circuit is always greater than the desired output voltage, the voltage developed across series resistor R_S is varied to obtain the desired value of output across the load resistance R_L.

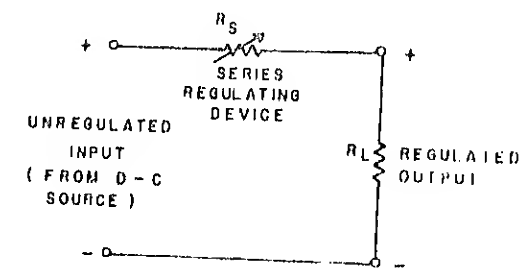


FIGURE 2-Simple series-type voltage-regulator circuit.

If the input voltage to the regulator circuit decreases, the voltage across load resistor R_L and variable resistor R_S also decreases. To counteract this voltage decrease, the resistance of variable resistor R_S is decreased so that a smaller voltage is developed across R_S, and the voltage across the load resistor returns to its former value. Conversely, if the input voltage to the regulator circuit increases, the voltage across load resistor R_L also increases. To counteract this voltage increase, the resistance of R_S is increased so that a larger voltage drop occurs across R_S, and the voltage across the load returns to its former value.

In a practical transistorized series regulator, the series regulating device must be capable of carrying the full-load current of the regulator. Regulation is performed by sampling the output voltage taken from a voltage divider and comparing this sample voltage with a reference voltage. Any deviation from the desired output voltage when compared with the reference voltage represents an error voltage, which is amplified and used to control the series device. It is interesting to note that a simple shunt-type regulator, using a breakdown (zener) diode, is frequently employed as the reference-voltage source or as a preregulator in more complex series-type regulators.

From the analysis in the preceding paragraphs, it is obvious that the series-type (as well as the shunt-type) voltage regulator is essentially a voltage-divider circuit, with the output voltage produced across the load being essentially constant, regardless of input voltage or load current variations. The control action required to vary the series regulating device and, consequently, to produce a corresponding variable-voltage across R_S is completely automatic. This basic principle of voltage regulation is used in the transistorized, series-type voltage regulators to be described later in this information sheet.

Breakdown-diode shunt-type regulator (zener)

The breakdown-diode, shunt regulator is used as a voltage regulator where the load is relatively constant. This circuit is frequently used in more complex regulator circuits as a reference-voltage source and as a preregulator in transistorized series regulators.

Characteristics

1. Uses a breakdown, or zener, diode as a shunt regulating device.

2. Regulated output voltage to load is nearly constant, even though changes in input voltage or changes in load current occur.

3. Voltage-divider principle is employed, using a fixed resistor and a breakdown diode in series; regulated load is taken from across the diode.

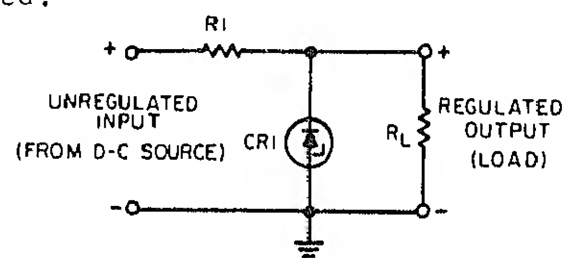
4. Variation in the basic circuit permits positive or negative voltages to be regulated.

The breakdown-diode regulator is the simplest form of shunt regulator. The regulator circuit consists of a fixed resistor in series with a breakdown, or zener diode. The regulated output voltage is developed across the diode; therefore, the load is connected across the diode. The regulator circuit develops a definite output voltage that is dependent upon the characteristics of the particular breakdown diode. Breakdown diodes are currently available with voltage ratings between 2 and 200 volts, in 5-, 10- and 20-percent tolerances, and with power dissipation ratings as high as 50 watts.

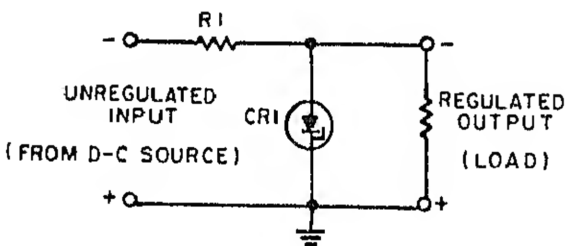
The breakdown, or zener, diode is a PN junction which has been modified during its manufacture to produce a specific breakdown voltage level; it operates with a relatively close voltage tolerance over a considerable range of reverse current. The breakdown diode is subject to a variation in resistance with a change in temperature of the diode. (A circuit that compensates for this change in resistance is discussed later.)

Circuit operation. In figure 3, schematics "A" and "B" illustrate a breakdown diode used in a basic voltage-regulator circuit. The two parts are identical in configuration with the electron-tube, gaseous-type voltage regulator. Resistor R_1 is the series resistor; semiconductor CR_1 is a breakdown, or zener, diode. The circuit in "A" provides regulation of a positive input voltage, while the circuit in "B" provides regulation of a negative input voltage.

The design of the breakdown-diode regulator differs from that of the gas-tube regulator circuit in that no "firing", or "ionizing", potential must be considered when the value of the series resistance is determined. It is likely that both the input voltage and the load current for the regulator will be subject to variation; therefore, the breakdown-diode regulator is designed to operate within the extremes to be encountered.



A



B

FIGURE 3 - Simple breakdown-diode regulator circuits.

The series resistor, R_1, needs only to stabilize the load; it compensates for any difference between the diode operating voltage and the unregulated input voltage. The value of the series resistor depends upon the combined currents of the breakdown diode and the load. The series resistor is generally chosen with the following factors in mind: the minimum value of input voltage (unregulated), the maximum value of load current, the minimum value of breakdown-diode current, and (knowing the diode characteristics) the value of the highest voltage to be developed across the breakdown diode and its parallel load resistance. Once the value of series resistor R_1 is determined, the maximum power dissipation in the diode can be determined by considering the maximum value of input voltage (unregulated), the minimum value of load current, and the minimum value of voltage developed across the diode (using the value of series resistance established for R_1). In order to obtain stable operation, the breakdown diode must be operated so that its reverse current falls

within its minimum and maximum ratings for the specified voltage. It is important to note that in no-load conditions, the breakdown diode must dissipate the full output power; therefore, this regulator circuit is never used in applications where a no-load condition is likely to exist. Instead,the breakdown-diode regulator is most often used in applications where the output voltage is fixed and the load current is relatively constant.

If the input voltage to the regulator circuit decreases, the voltage decrease appears across the breakdown diode, CR_1, and immediately the current through the diode decreases. Thus, the total current through series resistor R_1 decreases, and the voltage developed across R_1 decreases proportionately, so that for all practical purposes the output voltage across the load resistance (and breakdown diode) remains the same. Conversely, if the input voltage to the regulator circuit increases, the voltage increase appears across the breakdown diode, and immediatley the current through the diode increases. Thus, the total current through series resistor R_1 increases, and the voltage developed across R_1 increases proportionately, so that for all practical purposes the output voltage across the load resistance (and breakdown diode) remains the same. Conversely, if the input voltage to the regulator circuit increases, the voltage increases appears across the breakdown diode, and immediately the current through the diode increases. Thus, the total current through series resistor R_1 increases, and the voltage developed across R_1 increases proportionately, so that for all pactical purposes the output voltage across the load resistance (and diode) remains the same.

If the current drawn by the load resistance decreases, the total current drawn from the input source does not change. Instead, a corresponding increase in current through the breakdown diode occurs and the current drawn from the source remains constant, so that the output voltage across the load resistance remains constant.

Environmental temperature extremes, as well as junction temperature changes, may result in variations of the internal impedance of the breakdown diode, which, in turn, results in changes of the output voltage. Thus, in practical circuits, provisions must be made to compensate for any variation of the impedance of the breakdown diode. The temperature coefficient of resistance of the breakdown diode is normally several times larger than the negative temperature coefficient of resistance of either the forward-biased or reversed-biased junction diode. One commonly used method of temperature compensation used to obtain a zero coefficient of resistance over a wide range of temperature is to connect negative-temperature devices, such as forward-biased diodes or thermistors, in series with the breakdown diode. This method is illustrated in figure 4.

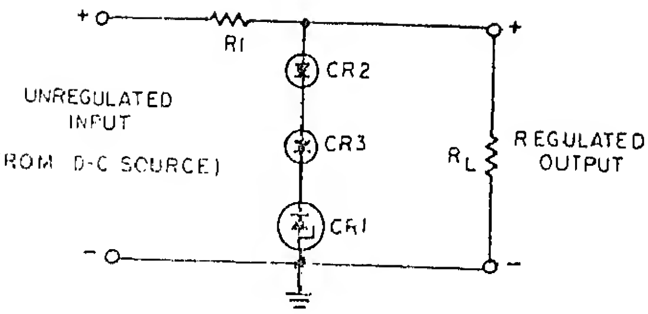


FIGURE 4 - Temperature-compensated voltage-regulator circuits.

The negative temperature coefficent of resistance of diodes CR_2 and CR_3 in series equals the positive temperature coefficient of resistance of the breakdown diode, CR_1. If diodes CR_2 and CR_3 are forward biased, the voltage drop across them will be kept to a minimum and, consequently, will have negligible effect on the value of the output voltage.

When the voltage-regulator circuit is temperature-compensated, as described above, the total resistance of CR_1, CR_2, and CR_3, in series, remains constant over a wide range of temperatures. The end result is a constant-voltage output, even though temperature, applied input voltage, or load current may change during operation.

Breakdown diodes are generally used as the reference-voltage source in the more complex transistorized regulators, because the breakdown voltage of a breakdown diode is relatively constant over a wide range of reverse current.

Series-transistor regulator

This regulator is used when it is necessary that the voltage supplied to the load resistor (voltage developed across R_L) remain relatively constant under varying load conditions. Figure 5 shows simplified drawings of the series-transistor regulator. Figure 5(A) shows a regulator for a positive supply voltage, and 5(B) shows a regulator for a negative supply voltage. The polarity of the supply to be regulated will determine the type of transistor to be used.

The positive regulator in "A" uses an NPN transistor as the regulator. The collector of the regulating transistor is connected to the unregulated power supply. For proper bias on an NPN transistor, a positive potential must be applied to the collector. The base must be negative in relation to the collector (or less positive). The emitter must be the most negative (or least positive) potential on the transistor. A constant (reference) potential is maintained on the base. As a result, the transistor has forward bias, emitter to base, and reverse bias, collector to base.

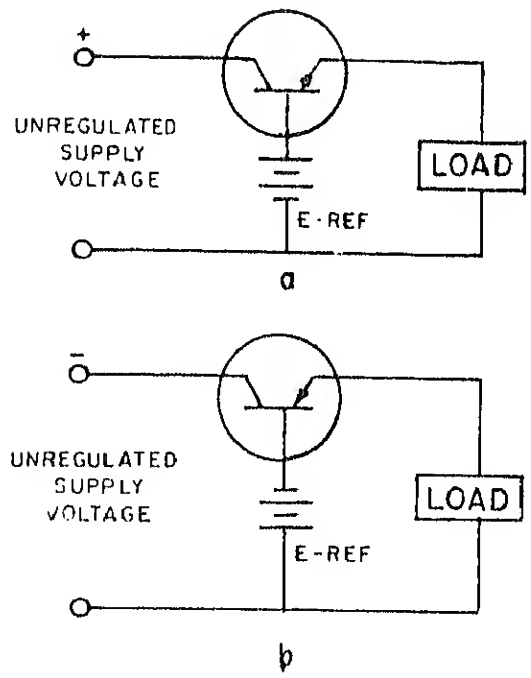


FIGURE 5 - Series-transistor regulators.

Reversing the applied polarities to the PNP transistor in figure 5(B) will apply the proper polarities for correct biasing to that transistor. To understand the regulating action, think of the transistor as replacing resistor R_S shown in figure 2. With forward bias applied to the emitter-base junction, the transistor conducts, causing part of the unregulated supply voltage to be developed from collector to emitter across the transistor. The rest of the unregulated supply voltage is developed across the load. The voltage developed across the load is the regulated voltage. To change the conducting resistance of the transistor, it is necessary to change the forward bias. An increase in forward bias causes an increase in conduction and therefore a decrease in conducting resistance. A decrease in forward bias causes an increase in conducting resistance. Since the base potential is held constant by the battery, the only change in bias can be caused by an attempted change in load potential, or the regulated supply potential at the emitter.

A change in forward bias, then, gives the same result as turning the rheostat arm in the circuit illustrated in figure 2. To illustrate this point, consider an increase in load current. This increase is caused by a decrease in load resistance (as when switching in another parallel path for current). Load voltage tends to decrease with load resistance. This is seen as a change in forward bias on the regulator transistor. Since the emitter voltage is decreased, the forward bias is increased. As a result, the transistor (in series with the load) conducts the new higher load current, and the conducting resistance of the transistor decreases. The decrease in resistance causes less of the supply voltage to be developed across the transistor, leaving nearly the same voltage available to the load that it had prior to the load change.

Now consider an increase in unregulated supply voltage. It has been shown by transistor characteristics in previous lessons that a change in collector voltage has negligible effect on collector current. The regulated voltage, as a result of no change in current through the collector (therefore, through the transistor), will not be varied.

The transistor used as a regulator must be capable of handling the load current safely. Generally, a power transistor is used because of the need to handle the high load currents. If a single transistor will not handle all the current, transistors may be placed in parallel.

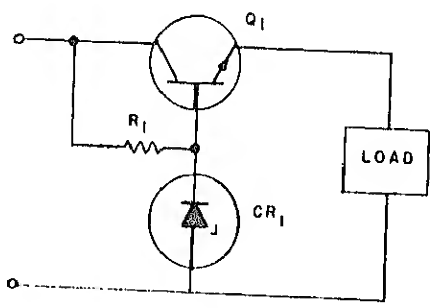


Figure 6

Figure 6 shows the method used to eliminate the battery, shown as a reference in figure 5. A zener diode and a series-limiting resistor replace the battery. The zener or breakdown diode, because of its constant voltage characteristic in its reverse breakdown region, maintains a constant voltage on the base of the regulator transistor. The circuit operation is identical with that previously described.

<u>Shunt-detected series voltage regulator</u>

It is sometimes necessary to regulate the load voltage to a much closer tolerance than can be achieved by the basic series regulator. A more sensitive control circuit must therefore be used to control the foward bias; hence, the conducting resistance of the control regulator is used. Figure 7 shows the basic shunt-detected series voltage regulator circuits for controlling positive and negative supply voltages. Figure 7(A) is a regulator for a positive supply, while the regulator in 7(B) regulates a negative supply.

circuits is the regulating transistor. Note that Q_1 is in
the load. The control circuit for each regulator consists
R_2, R_3, R_4, R_5, and R_6. The capacitor C_1 is a
levice to reduce noise or ripple on the d-c load
he regulator) transistor is usually a power tran-
the load current, plus part of the current drawn
it. Q_2 is usually a high-gain transistor (small
nay react to very small changes in the load
eference diode to hold the emitter potential of Q_2
e. Resistor R_1 acts as the collector load
trol transistor. The difference in potential
base junction of Q_1 is the same as the difference

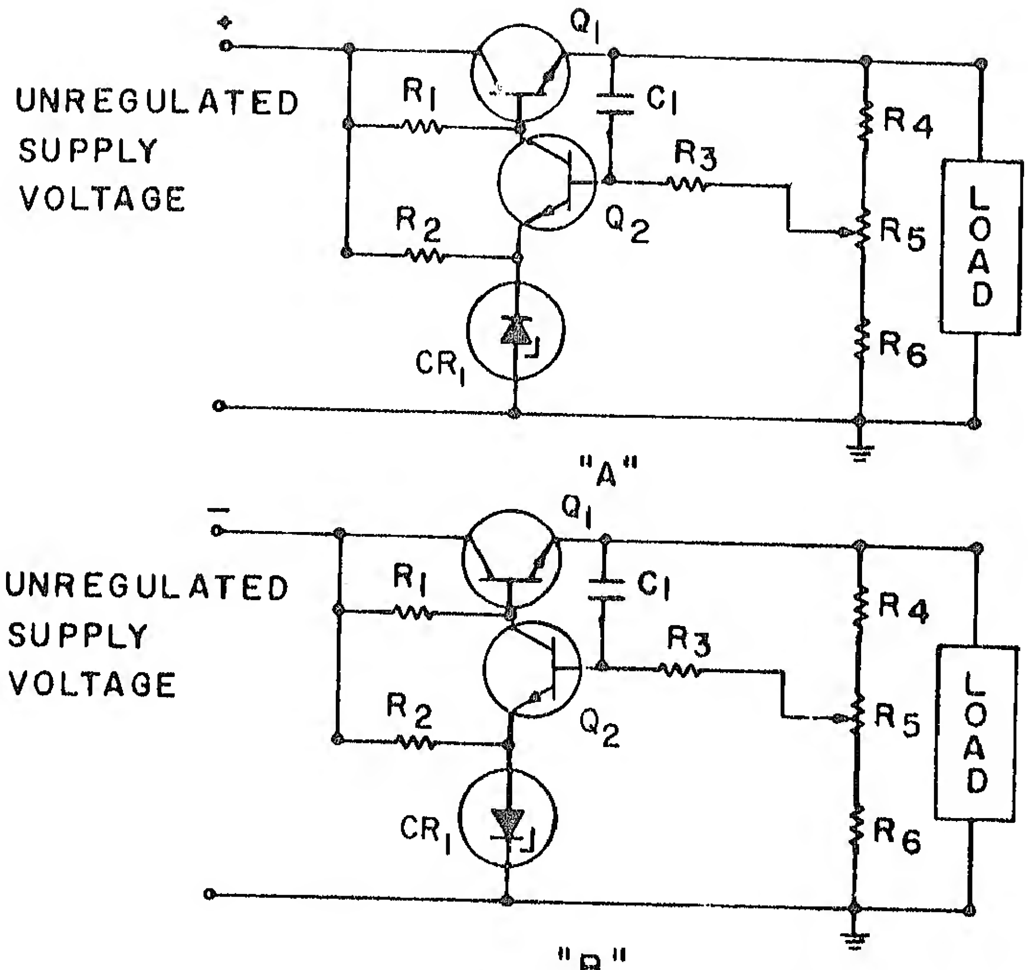


FIGURE 7 - Shunt-detected series voltage regulator: positive input (A). Negative input (B).

between the collector voltage (V_C) and the regulated supply voltage of Q_2. R_3 is current-limiting resistor for the base of Q_2. The voltage-divider network consisting of R_4, R_5, and R_6 develops the regulated voltage (in parallel with the load) and selects a portion of this voltage for the base of Q_2. The forward bias for Q_2 is selected by the voltage divider. Since the potential on CR_1 does not change, the only way to change the forward bias on Q_2 is to have a change in load voltage or change the position of the potentiometer arm on R_5.

In a cycle of circuit operation, suppose that the load voltage begins to increase. Since the voltage divider (composed of R_4, R_5, and R_6) is in parallel with the load, this increase will fall across the voltage divider, which will cause an increase at the base of the control transistor Q_2. The increase on the base of Q_2 will increase the difference in the base potential and the emitter potential and increase forward bias on Q_2, which will cause conduction in Q_2 to increase. The increase in current through the collector will also be through R_1. An increase in current through R_1 will cause the collector voltage of Q_2 to decrease. Since the voltage from the collector of Q_2 to ground is the base voltage of Q_1, then the base voltage of Q_1 will decrease. This decrease in voltage on the base of Q_1 is seen as a decrease in its forward bias. A decrease in

forward bias effectively increases the conducting resistance of Q_1. Q_1 then develops more voltage across its higher resistance and returns the load voltage to practically the same value it had prior to its attempted increase. Since Q_2 is a high-gain transistor, it takes a very small change in base voltage to control what could have been a relatiavely large change in load voltrage.

Gas-tube regulator

The gas-tube regulator is one of the simplest types of voltage regulators. The regulator circuit consists of a fixed resistor in series with a cold-cathode, gas-filled regulator tube. The regulated output voltage is developed across the regulator tube; therefore, it is across this tube that the load is connected.

The regulator circuit develops a definite output voltage, which is dependent upon the type of gas tube used in the circuit, provided the variation in load current is within the operating range of the type of tube used. Gas tubes are rated according to the voltage across the tube during normal operation and according to the maximum permissible current through the tube. Typical approximate operating voltage ratings for cold-cathode, gas-filled tubes are 75, 90, 105, and 150 volts d-c; typical maximum current ratings are 30, 40, and 50 milliamperes.

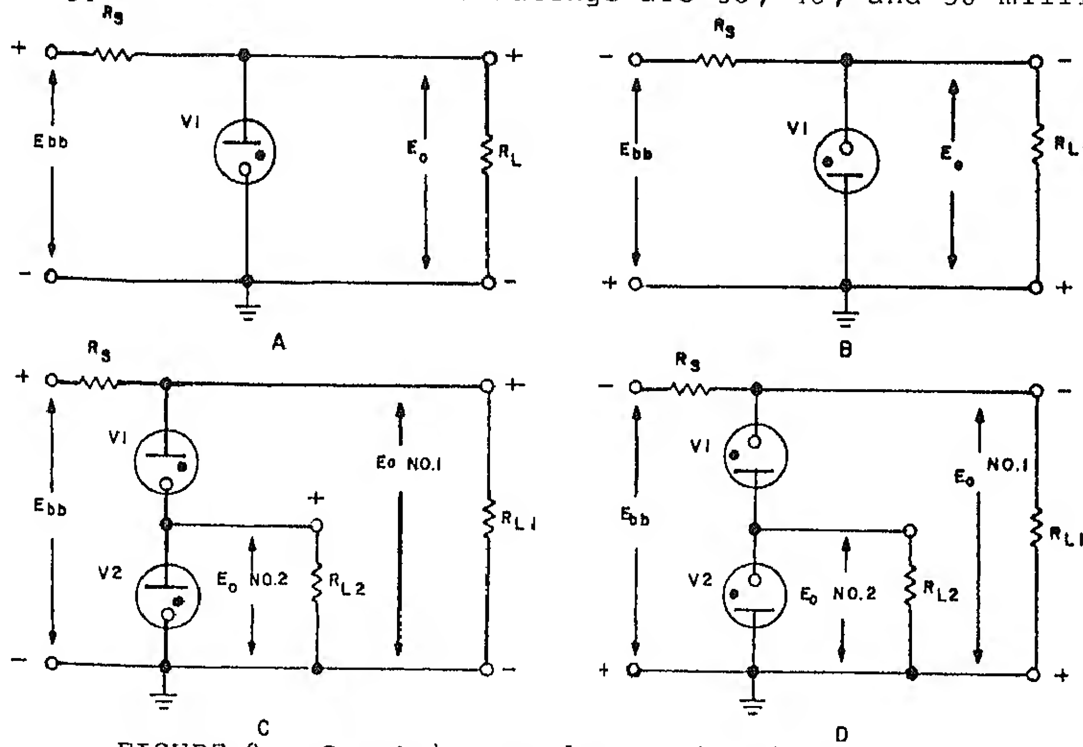


FIGURE 9 - Gas-tube regulator circuits.

Figure 9, parts A and B, illustrate a gas tube used in a basic voltage-regulator circuit. Resistor R_S is the series resistor; electron tube V_1 is the gas-filled regulator tube. The circuit in part A provides regulation of a positive input voltage, while the circuit in part B provides regulation of a negative input voltage. Several regulator tubes may be connected in a series combination, if desired, to obtain a higher regulated output voltage. In the accompanying circuit schematic, parts C and D illustrate two regulator tubes in series. The circuit in part C provides regulation of a positive input voltage, while the circuit in part D provides regulation of a negative input voltage. Intermediate regulated voltages can be obtained from the junction of the regulator tubes in the latter two circuits (or from the junction of any series combination of regulator tubes), provided that the current drain of the associated load is kept low.

The cold-cathode, gas-filled regulator tube is a two-electrode tube with a cathode and plate. The evacuated tube contains a small amount of gas, such as neon, which is sealed inside the tube. When sufficient voltage is applied to the tube, ionization of the gas molecules occurs and is responsible for the current passing through the tube during operation. If a gas tube is connected directly across a source of voltage that is high enough to ionize the gas, the current will immediately increase to such proportions that the tube may be damaged. The use of a series resistance is essential, therefore, to limit the current through the tube.

There are two separate voltages to be considered in discussing the conditions under which the regulator tube will ionize and operate--the breakdown, or firing, voltage and the operating voltage. The breakdown (or firing) voltage is the value of voltage at which the gas becomes ionized and begins to pass current. Below this starting voltage, the gas will not ionize and current will not pass through the tube. The operating voltage is the value of voltage at which the tube will remain ionized after having started. There is a considerable difference between the supply voltage and the voltage at which the regulator operates. This difference is compensated for by the series resistor, R_S, which also serves to stabilize the load.

The value of the series resistor depends upon the maximum d-c voltage input to the regulator circuit, the regulated d-c output voltage, and the combined currents of the regulator tube and the load. The resistor is generally chosen to be of sufficient resistance to limit the current through the regulator tube to a value that is always less than the rated maximum operating current. The current through the regulator tube at the instant of ionization and before the load current has risen to its normal value may initially exceed the maximum value; however, as soon as the load current rises to its normal value, the regulator tube current drops to a value that is within operating limits, because of the series resistance in the circuit.

The ionization of the gas within the tube changes, depending upon the applied voltage; as a result, the internal resistance of the regulator tube changes. When the applied voltage increases to lower the tube resistance, a larger current is passed. Conversely, when the applied voltage decreases, the ionization of the gas decreases to increase the tube resistance, and a smaller current is passed.

In the circuit schematic, note that the load current and the regulator tube current both pass through the series resistor, R_S. If the d-c input voltage to the regulator circuit drops, the voltage across the regulator tube also drops momentarily, at which time the gas within the tube deionizes slightly and less current passes through the regulator tube. Therefore, the current through the series resistor decreases by the amount of the decrease in the regulator tube. Since the current through the series resistor decreases, the voltage developed across the resistor also decreases and the output voltage delivered to the load increases to return to its original value. In a similar manner, if the input voltage to the regulator circuit increases, the voltage across the regulator also increases momentarily; at which time, the gas within the tube is further ionized and more current passes through the regulator tube. Thus, the current through the series resistor is increased. Since the current through the series resistor increases, the voltage developed across the resistor also increases, and the output voltage delivered to the load decreases to return to its original value. When the value of the series resistance is the correct value for the load to be regulated, the output voltage is held nearly constant by the action of the regulator tube. As just described, this action depends upon the fact that changes in the ionization of the gas within the tube vary the amount of tube conduction.

The discussion above is based on the assumption that a change occurred in the d-c input voltage applied to the regulator circuit also compensates for changes occurring in the load current. If the load current should increase, the voltage developed across the series resistor, R_S, would immediately increase. As a result, the voltage across the regulator tube would decrease momentarily. Gas within the tube would deionize slightly, and less current would pass through the regulator tube. Therefore, the current through the series resistor decreases by the amount of the decrease in the regulator tube. Since the current through the series resistor decreases, the voltage developed across the resistor also decreases, and the output voltage delivered to the load increases, returning to its original value. In a similar manner, if the load current should decrease, the voltage developed across the series resistor would immediately decrease. As a result, the voltage across the regulator tube would increase momentarily, the gas within the tube would be further ionized, and more current would pass through the regulator tube. Thus, the current through the series resistor would increase. Since the current through the series resistor increases, the voltage developed across the resistor also increases, and the output voltage delivered to the load decreases, returning to its original value. It is obvious, then, that the output voltage is held nearly constant by action of the regulator tube when changes occur in the load current.

The d-c input voltage required to causes ionization of the regulator tube when the circuit is first energized is approximately 30 percent greater than the operating voltage specified for the regulator tube. The output voltage of the regulator circuit quickly drops to the operating value of the regulator tube as soon as the tube ionizes and begins to conduct, which causes a voltage drop to appear across the series resistance, R_S. In order to obtain stable operation, the regulator tube must be operated so that it is ionized at all times, and its operating current must fall within specified maximum and minimum current ratings. If, for some reason, the operating current exceeds the specified maximum current rating or if the voltage across the tube is excessive, the tube will become highly ionized, will lose its ability to regulate, and may be permanently damaged. Conversely, if the operating current drops below the specified minimum current rating (approximately 5 milliamperes), the tube will become deionized and will no longer regulate the output.

Also, if the voltage across the regulator tube drops below the specified operating voltage to a value that is approximately 70 percent of the breakdown (or firing) voltage, the tube will become deionized.

The value of the series resistor, R_S, can be approximated by using the following formula:

$$R_S = \frac{E_{bb} - E_o}{I_p + I_{load}}$$

where E_{bb} = unregulated d-c input (supply) voltage
E_o = regulated output voltage (to load)
I_p = regulator-tube current
I_{load} = load current

When operation of the regulator tube is desired at the midpoint of its rated current range, the value of the tube current used in the formula is given as:

$$I_p = \frac{I_{max} + I_{min}}{2}$$

where: I_{max} = rated maximum tube current
I_{min} = rated minimum tube current

In applications where a regulated voltage greater than the voltage rating of a single regulator rube is required, several regulator tubes may be connected in series to obtain regulation of the desired voltage. Furthermore, if the current drain of the load is kept low, an intermediate regulated voltage can be obtained at the junction of any two regulator tubes of the series. Figure 9, parts C and D, illustrates two regulator tubes connected in series. This circuit configuration permits a lower regulated voltage (E_o No. 2) to be taken from the d-c supply. Note that the current through regulator tube V_2 and the load current of the lower regulated voltage (E_o No. 2) must pass through regulator tube V_1; therefore, the load current of the lower voltage must be relatively small to prevent the combined currents from exceeding the maximum current rating of regulator tube V_1.

NOTETAKING SHEET 3.3.1N

POWER SUPPLY REGULATORS

REFERENCES:

1. Basic Electronics, Vol. I. NAVPERS 10087-C.

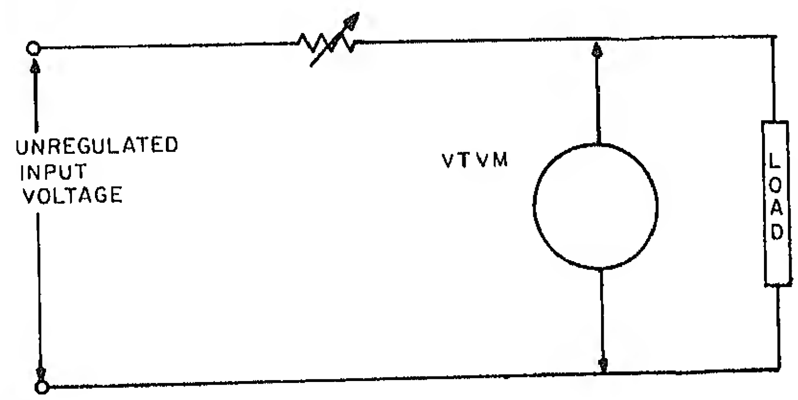
2. Electronic Circuits. NAVSEA 0967-P-000-0120. Chapter 3, pages 3-1 to 3-4, 3-16 to 3-25, and 3-51 to 3-53.

3. Slurzberg, Morris and William Osterheld. Essentials of Radio Electronics. Second Edition. McGraw-Hill, Inc., 1961

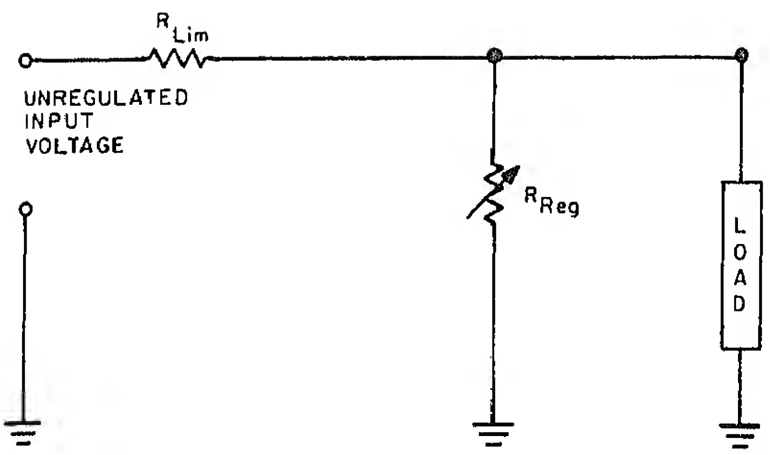
4. Slurzberg, Morris and William Osterheld. Essentials of Communication Electronics. Third Edition. McGraw-Hill, Inc., 1973.

A. Fundamental Regulators

1. Series regulator

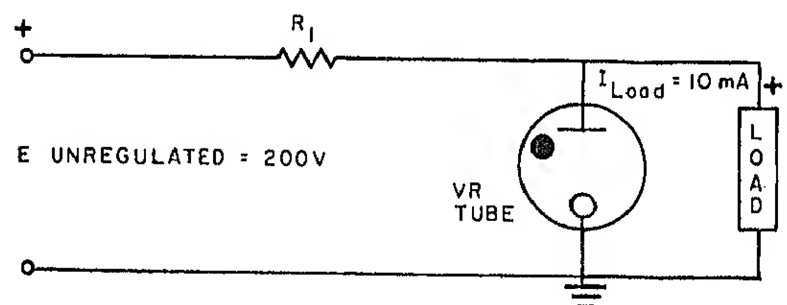


2. Shunt regulator



B. Gas-tube Voltage Regulator

1. Characteristics



2. Circuit operation

3. Mathematical analysis

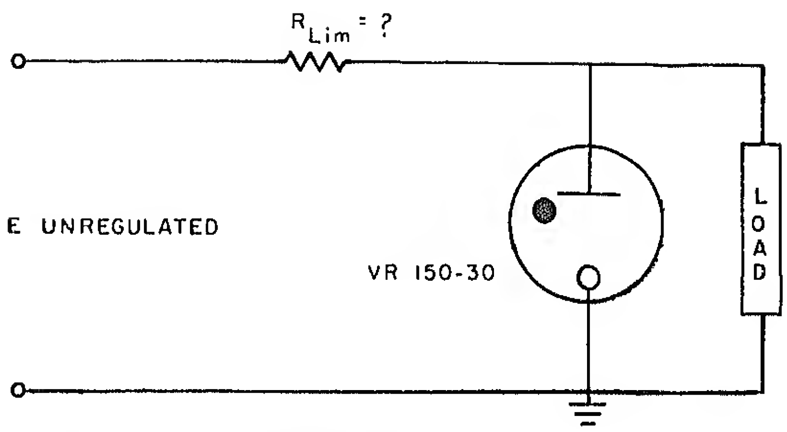
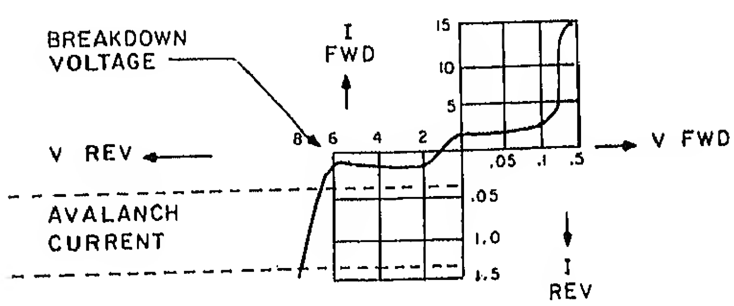


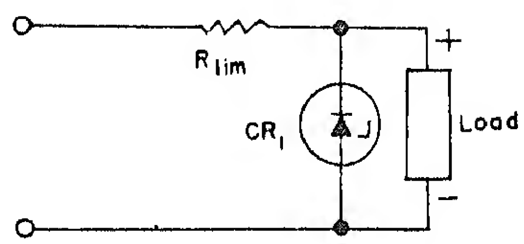
FIGURE 4 - GAS TUBE REGULATOR

C. Zener (breakdown) Diode Voltage Regulator

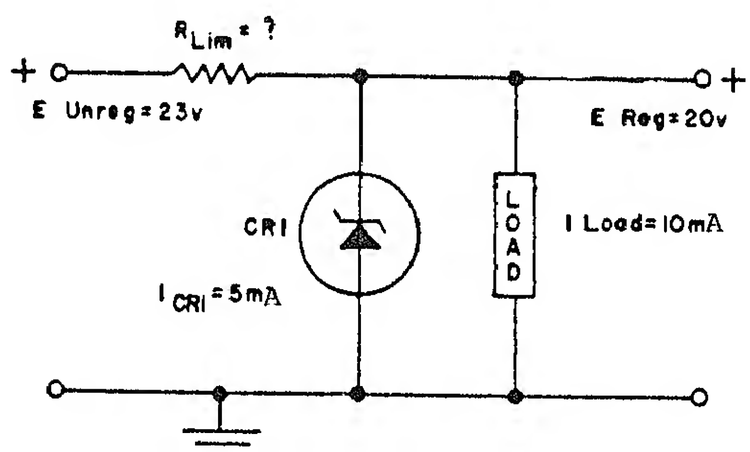
1. Characteristics



2. Circuit operation

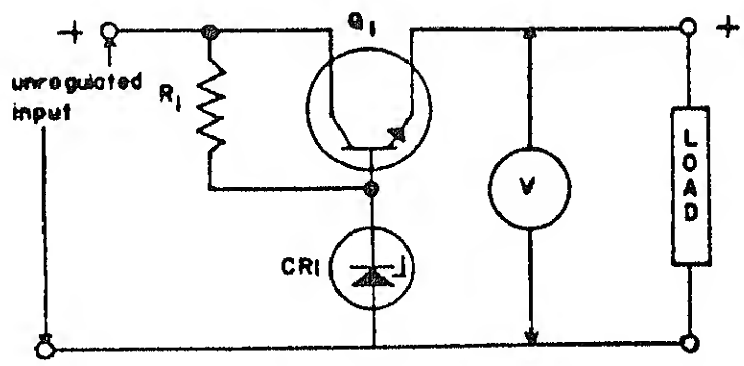


3. Mathematical analysis



D. Series-transistor Regulator

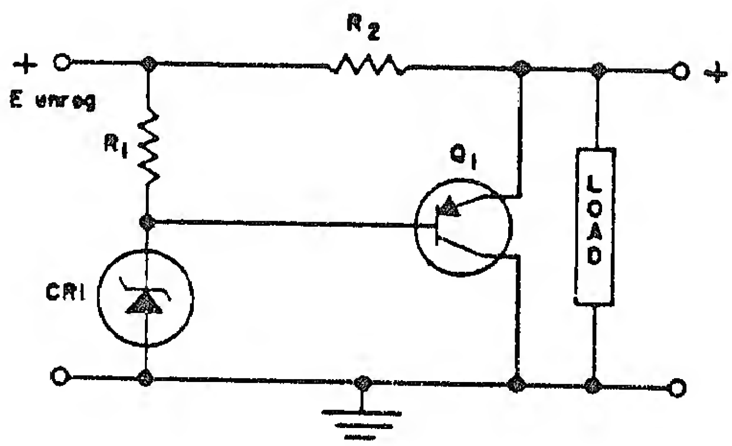
1. Characteristics



2. Circuit operation

E. Shunt-transistor Regulator

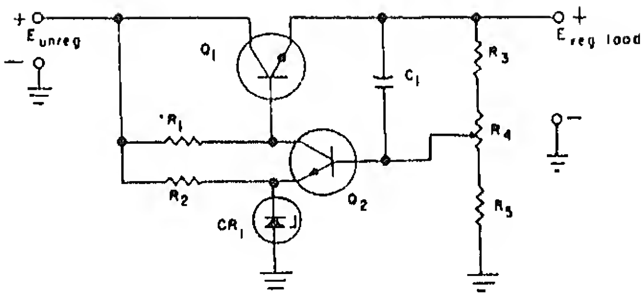
1. Characteristics



2. Circuit operation

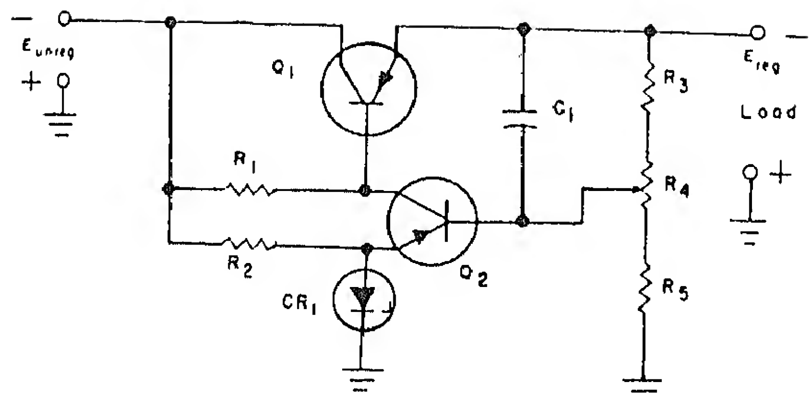
F. Shunt-detected Series Voltage Regulator

1. Characteristics



2. Circuit operation with a positive input

3. Circuit operation with a negative input



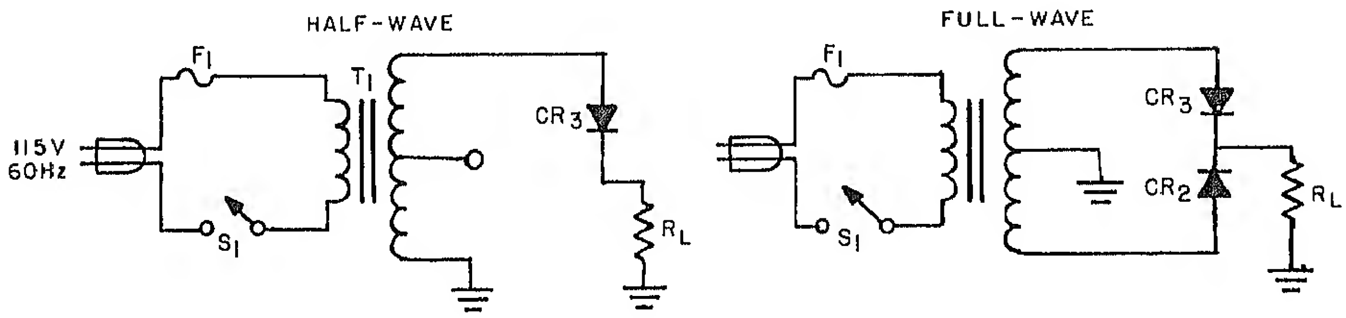
E_{unreg}
Q_1
C_1
R_3
E_{reg}
Load
R_1
R_4
R_2
Q_2
CR_1
R_5

NOTETAKING SHEET 3.3.2N

POWER SUPPLY (Circuit Operation)

Record all calculations, measurements, and waveforms as the instructor indicates during the lecture demonstration.

G. Power-supply Rectifier Operation



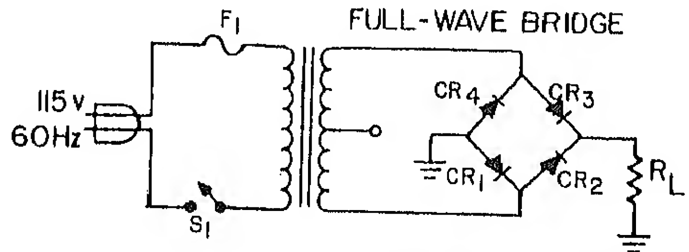
	HALF-WAVE	FULL-WAVE
Calculated E_{sec}		
Calculated E_{sec} pk		
Calculated E_{d-c}		
Measured E_{d-c}		
Measured E_{rip}		
Ripple freq.		
Input waveform		
Output waveform		

Review questions

1. Which power supply output would be easiest to filter?
   Answer: ______________________________

2. Why?
   Answer: ______________________________

Full-wave bridge rectifiers



FULL-WAVE BRIDGE

Calculated E_{sec}	
Calculated $E_{sec\ pk}$	
Calculated E_{d-c}	
Measured E_{d-c}	
Measured E_{rip}	
Ripple freq	
Input waveform	
Output waveform	

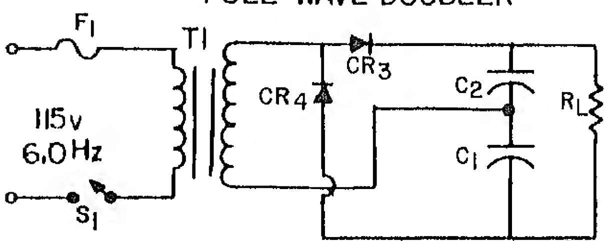
Review question

1. Compare the full-wave bridge rectifier to a half-wave and a full-wave rectifier in terms of E_{d-c} and ripple frequency.

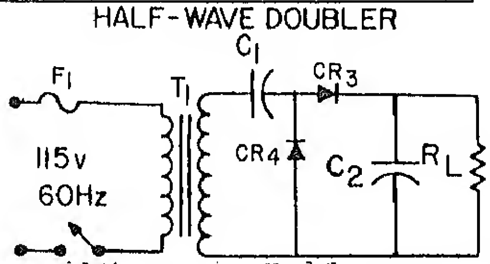
   Answer: ____

   ____

FULL-WAVE DOUBLER



HALF-WAVE DOUBLER



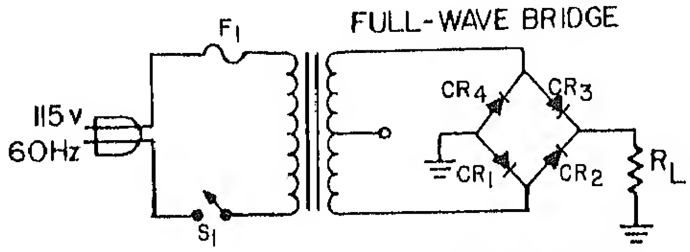
	Full-wave voltage doubler		Half-wave voltage doubler	
Calculated E_{sec}				
Calculated E_{sec} pk				
Calculated E_{d-c}				
Measured E_{d-c}				
E_{C1}	Calculated	Measured	Calculated	Measured
E_{C2}	Calculated	Measured	Calculated	Measured
Measured E_{rip}				
Ripple freq.				
Input wasveform				
Output waveform				

Review questions

1. Which power supply output would be easiest to filter?
   Answer: ______________________________

2. Why?
   Answer: ______________________________

Full-wave bridge rectifiers



FULL-WAVE BRIDGE

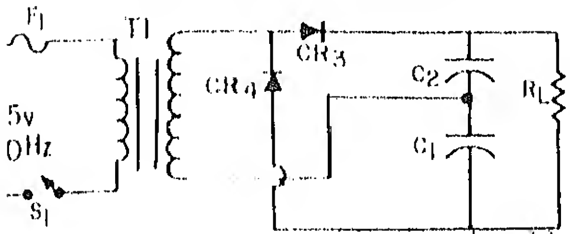
Calculated E_{sec}	
Calculated E_{sec} pk	
Calculated E_{d-c}	
Measured E_{d-c}	
Measured E_{rip}	
Ripple freq	
Input waveform	
Output waveform	

question

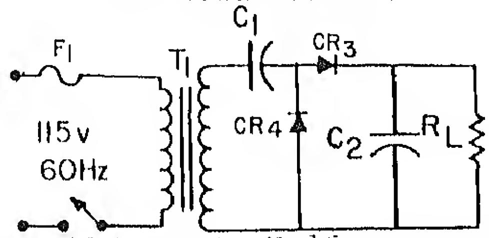
mpare the full-wave bridge rectifier to a half-wave and a ll-wave rectifier in terms of E_{d-c} and ripple frequency.

swer:

FULL-WAVE DOUBLER



HALF-WAVE DOUBLER



	Full-wave voltage doubler		Half-wave voltage doubler	
Calculated E_{sec}				
Calculated E_{sec} pk				
Calculated E_{d-c}				
Measured E_{d-c}				
	Calculated	Measured	Calculated	Measured
E_{C1}				
	Calculated	Measured	Calculated	Measured
E_{C2}				
Measured E_{rip}				
Ripple freq.				
Input waveform				
Output waveform				

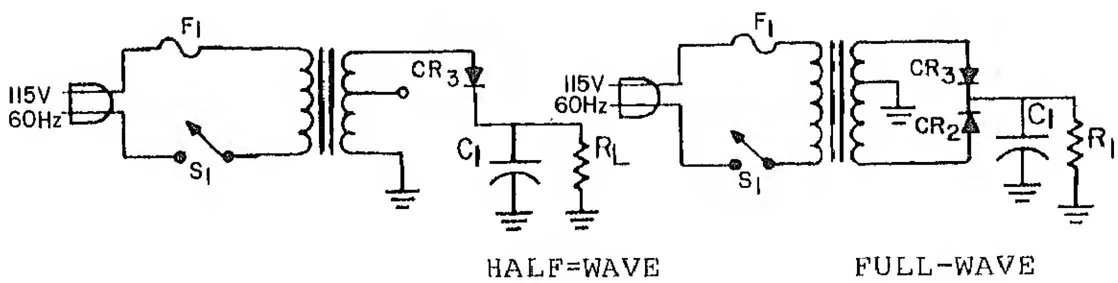
Review questions

1. What is the working voltage (WV) of the capacitors in the full-wave doubler?
   Answer: C_1=______________; C_2=______________.

2. What is the working voltage (WV) of the capacitors in the half-wave doubler?
   Answer: C_1=______________; C_2=______________.

H. Power-supply Filter Operation

Capacitive-input filters



Calculated E_{sec} pk		
Calculated E_{d-c}		
Measured E_{d-c}		
Measured E_{rip}		
Ripple freq.		
Input waveform		
Output waveform		

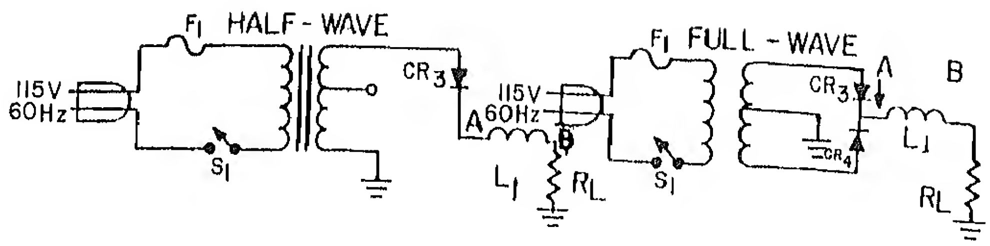
Review question

1. Compare the half-wave, capacitor-input, filtered power supply to the full-wave, capacitor-input, filtered power supply in terms of E_{d-c} and ripply frequency.

   Answer: ______________________________

   ____

Inductive-input filters



	HALF-WAVE			FULL=WAVE		
Calculated E_{d-c} A						
Measured E_{d-c}	A	B		A	B	
Measured E_{rip} at "A"						
Measured E_{rip} at "B"						
Ripple freq.						
Waveform at "A"						
Waveform at "B"						

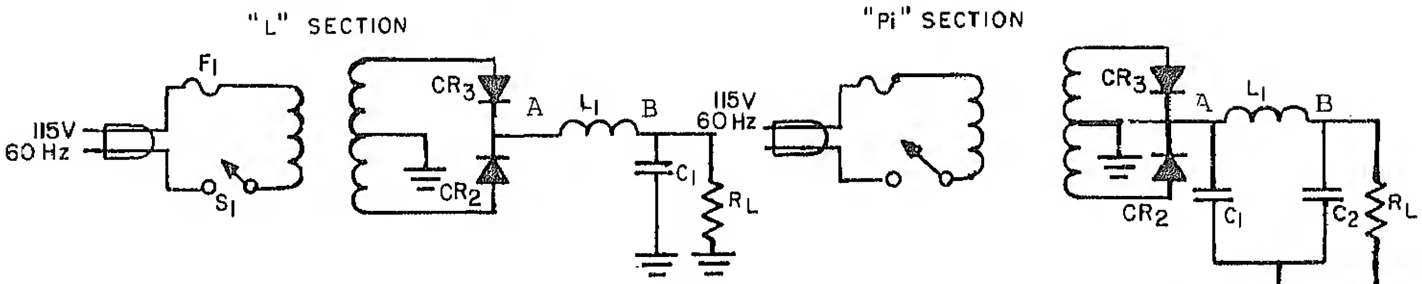
Review question

1. Compare the inductor-input filter, to the capacitor-input filter in terms of E_{d-c}, and voltage regulation characteristics.

   Answer: ____

   ____

L-section and Pi-section filters



L-section	AT POINT A	AT POINT B
Calculated E_{sec}=		XXXX
Measured E_{d-c}		
Measured E_{rip}		
Waveform		
Calculated % Ripple		
II-section		
Calculated $E_{sec\ pk}$ =		XXXX
Measured E_{d-c}		
Measured E_{rip}		
Waveform		
Calculated % Ripple		

Review questions

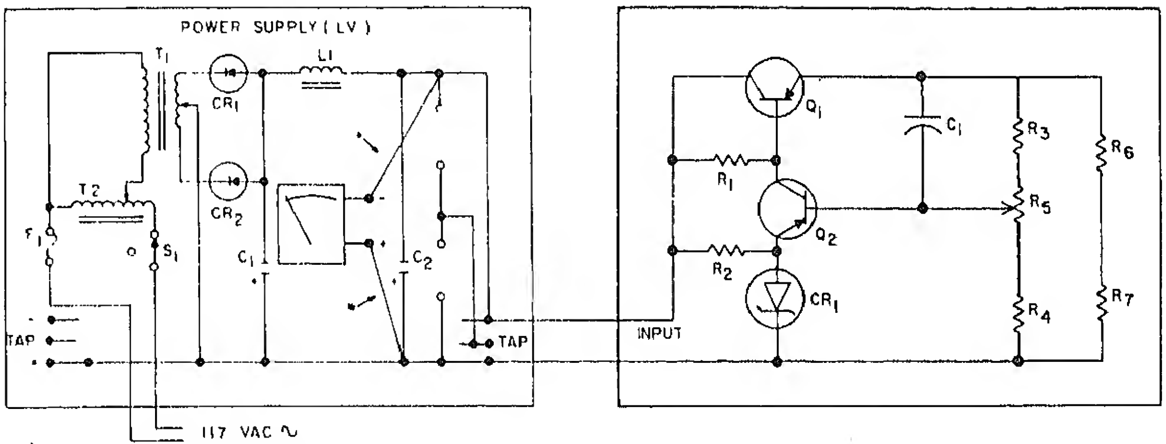
1. Which of the filters above provides the best filtering action?

   Answer:____________________________Why?____________________

2. Which of the filters above provides the highest E_{d-c}?

   Answer:.___________________________Why?____________________

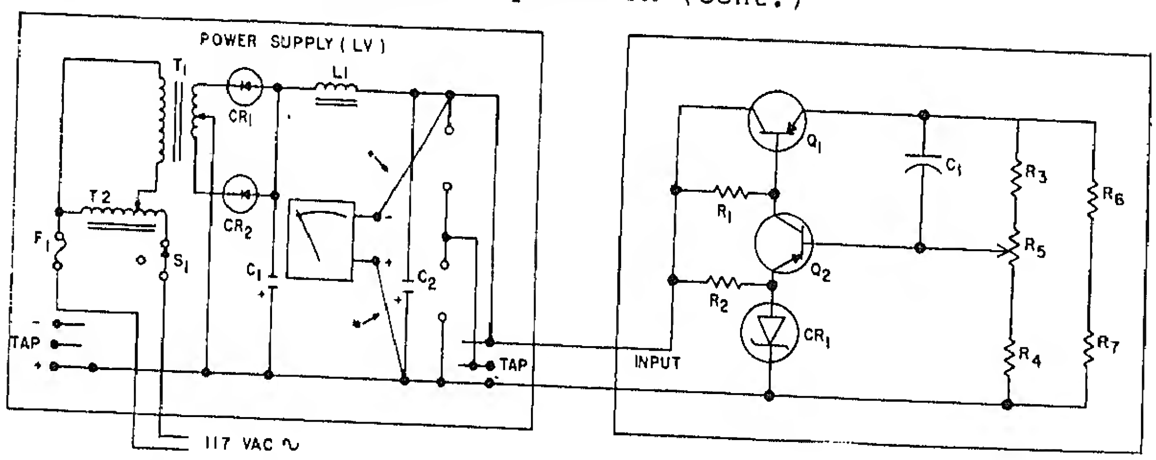
I. Power-supply Voltage Regulator Operation



Variations in $E_{unregulated}$

	Normal	Increase	Decrease
$E_{unregulated}$	-17 volts	-19 volts	-15 volts
Measured $E_{regulated}$			
Measured E_{Q1} (collector to emitter)			
Measured E_{R1} (collector load Q_2)			
Measured E_{CE1} (zener)			
Measured E_{R2} (R_{Lim})			

Power supply voltage regulator operation (cont.)



Variations in load and component values

	E_{reg} ↓ or ↑	Z_{Q2} ↓ or ↑	Z_{Q1} ↓ or ↑
Decrease load			
Increase load			
Move pot arm R_5 up			
Move pot arm R_5 down			
Open R_4			
Open R_3			
Open C_{R1} (zener)			
Open Q_2			
Open R_1			

Review questions

1. What is the purpose of a voltage regulator?
   Answer: ____.

2. What is the purpose of the zener diode in a shunt-detected series voltage regulator?
   Answer: ____.

3. Refer to the voltage regulator diagram. What will happen to $E_{regulated}$ if R_4 fails open?
   Answer: ____.

4. Refer to the voltage regulator diagram. What will happen to the conducting impedance (internal resistance) of Q_1 and Q_2 if the load decreases?
   Answer: Q_2's impedance ____________________.
   Q_1's impedance ____________________.

INFORMATION SHEET 3.4.1I

AUDIO-FREQUENCY POWER AMPLIFIERS

INTRODUCTION

In general, the final stage of a series of audio amplifiers is called the power stage. This stage differs from the preceding stages in that it is designed to obtain maximum a-c power out rather than maximum voltage gain. The purpose of a power amplifier is to efficiently deliver distortion free power to the load. Some distortion of the audio waveforms always takes place, but in a properly designed circuit this distortion will be held to a minimum.

REFERENCES

1. Basic Electronics, Vol. I. NAVPERS 10087-C. Chapter 13.

2. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 5.

3. Shrader, Robert. Electronic Communications. Fourth Edition/ N.Y., McGraw-Hill Book Company, 1980. Pages 296 to 301.

GENERAL INFORMATION

There is no distinct, clear-cut line at which an amplifier ceases to be a voltage amplifier and becomes classified as a power amplifier. You are already aware of the fact that the amplifiers you have previously studied are capable of both voltage and power gains. There are, however, very distinct differences in the circuitry of voltage and power amplifiers.

Voltage amplifiers are designed to deliver a large voltage to a given load impedance (Z_L). A power gain usually results but is of secondary importance. Power amplifiers, on the other hand, are designed to deliver a large power to a given load impedance (Z_L). Normally voltage or current gain occurs, but again, this is of secondary importance.

The operations of both types of circuits are similar, but the outputs are determined by the device used (type of transistor) and the circuitry. The voltage amplifiers are characterized by transistors that have relatively low-output currents. These currents, however, are fed to load impedance (Z_L) that are very large, when compared with the output impedance of the transistor; therefore, we have a circuit that produces a large voltage across the load impedance. Because of the small amount of current, the transistor dissipates very little power.

Power amplifiers are characterized by transistors that provide a large output current. This current works into a low-load impedance. The large current into the load impedance provides a large power (I^2Z_L) delivered to the load impedance. Because of the large amount of current flowing in the transistor of a power amplifier, care must be taken to ensure that the maximum collector power dissipation rating is not exceeded. This could result in irreparable damage to the device.

It should be apparent now that transistors do not generate power; in fact, they dissipate power. If the transistor does not generate power, what then does it do? Transistors are merely control devices that permit the conversion of the d-c power applied to the circuit to useful a-c power in the load impedance (Z_L). Because of the resistance of the transistor and the current through it, the device dissipates power; therefore, it can never be 100 percent efficient.

EFFICIENCY

The percentage of efficiency is a measure of how well a power amplifier converts d-c power to useful a-c power. The formula for percentage of efficiency is

$$\% \text{ of efficiency} = \frac{P_{a-c} \quad \text{(output power)}}{P_{d-c} \quad \text{(input power)}} \times 100$$

The formula as stated is basic and is used to express several different values of efficiency for any given amplifier.

In the transistor circuit, we have percentage of collector efficiency, percentage of collector circuit efficiency, and percentage of circuit efficiency. Each of these expresses a different value of efficiency. Regardless of which value of efficiency is being expressed, the value of P_{a-c} in the formula is the same. P_{a-c} may be determined by any of the basic power formulas:

$P_{a-c} = I_{sig} \times E_{sig}$; $P_{a-c} = (I_{sig})^2 \times Z_L$;

$$P_{a-cE} = \frac{E_{sigE})^2}{Z_L}$$

The portion of the formula that determines the type of efficiency is the value representing the d-c input power.

The "percentage of collector efficiency" is the value most often used, and it expresses a higher percentage value than any other.

$$\text{Percentage of collector efficiency} = \frac{P_{a-c}}{P_{d-c}} \times 100$$

The value of d-c power is determined by the voltage across the transistor, or from collector to emitter (V_{CE}) times the collector current (I_C) $P_{d-c} = V_{CE} \times I_C$.

$$\text{Percentage of collector efficiency} = \frac{P_{a-c}}{V_{CE} \times I_C} \times 100$$

The percentage of collector circuit efficiency is determined by using the collector supply voltage (V_{CC}) times the collector current (I_C)/

$$\text{Percentage of collector circuit efficiency} = \frac{P_{a-c}}{V_{CC} \times I_C} 100$$

The percentage of circuit efficiency is the lowest percentage figure for any given amplifier. The value of P_{d-c} used here is the collectsor supply (V_{CC}) times the collector supply current (I_{CC}).

$$\text{Percentage of circuit efficiency} = \frac{P_{a-c}}{V_{CC} \times I_{CC}} \times 100$$

Although single-ended power amplifiers are not too commonly found with resistive loads, figure 1 is used to illustrate the difference between the values of efficiency.

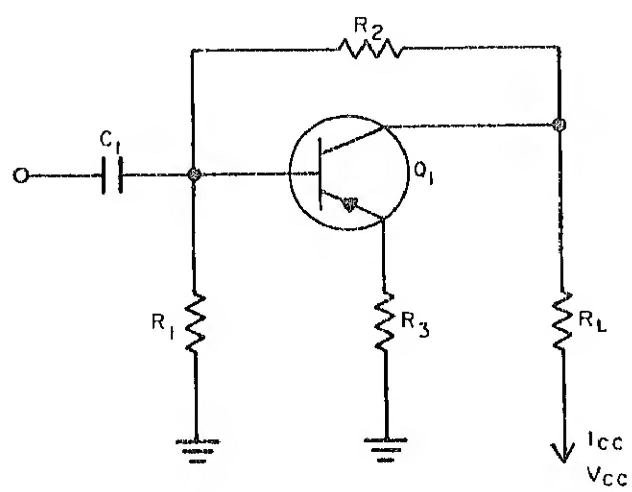


FIGURE 1 - Single-ended power amplifier.

It is evident that when using V_{CC} x I_{CC} for PO_{d-c} to find circuit efficiency, the total d-c power input to the circuit is being used, therefore yielding the lowest value of efficiency. When determining collector circuit efficiency, where V_{CC} x I_C is used for determining P_{d-c}, the d-c power dissipated by R_1 and R_2 is eliminated, which yields a higher percentage. When determining collector efficiency, where V_{CE} x I_C is used for P_{d-c}, all d-c power dissipation is eliminated, except that of the transistor itself. This, of course, yields the highest percentage of efficiency.

As stated, the most often used figure is the collector efficiency, but the figures for circuit efficiency give a better overall picture of the circuit's ability to convert d-c power to a-c power. In actual cases, none of the figures for efficiency will exceed 50 percent. In fact, percentage of efficiency will always be less than 50 percent. The maximum theoretical collector efficiency is 50 percent; and of course, collector efficiency is the highest percentage figure.

In determining the maximum theoretical efficiency, it is necessary to drive the transistor to its limits. It should be noted at this time that the distortion of the collector current cannot be tolerated if there is to be any fidelity. Another factor to consider here is that the average value of collector current has been reduced under a signal condition. If a power amplifier is to be used when fidelity is of importance, it is necessary to sacrifice output power and efficiency.

DISTORTION IN A TRANSISTOR POWER AMPLIFIER

Distortion comes from two of the transistor's characteristics and, under certain conditions, from other circuit components.

Figure 2 shows the uneven spacing between the VCE-IC curves. This characteristic is responsible for the distortion called H2, or even-order (second-order) harmonic distortion. The nonlinear input impedance characteristic also contributes to H2 distortion.

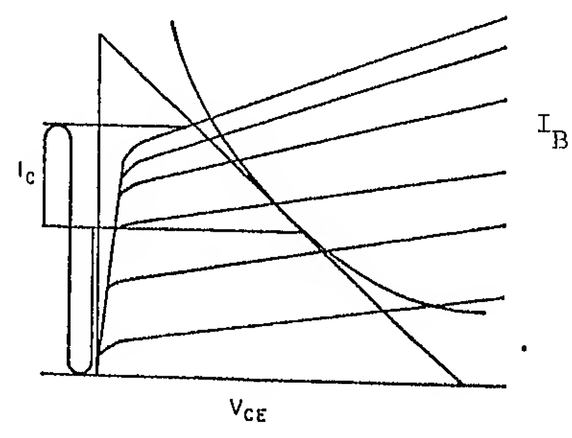


FIGURE 2 - V_{CE}-I_C curves

The graph in figure 3 is a plot of the V_{BE} versus the I_B, or a plot of the input resistasnce. It is plainly evident that a symmetrical sine wave of voltage applied to the input (voltage, emitter to base) does not cause a linear change of base current (i_b).

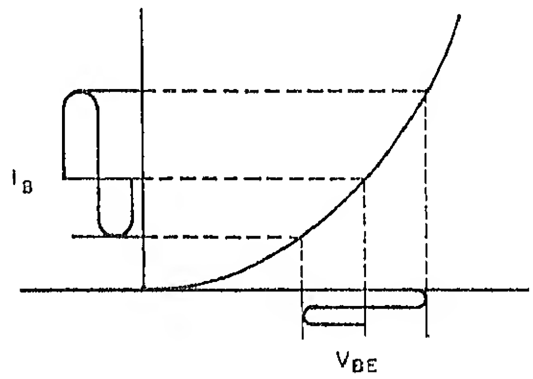


FIGURE 3 - V_{BE} versus the I_B.

Transformer Coupling

Single-ended power amplifiers are rarely terminated in resistive load impedances; a resistor in the collector circuit of a transistor would dissipate power, even in a static state. Although average collector current varies under signal conditions, the resistor would still dissipate d-c power. This represents a drastic reduction in efficiency; and in order to avoid this, transformer coupling is used. By using a transformer, the only resistance in the collector circuit is the very small d-c resistance of the primary winding. Thus, the d-c power dissipation is greatly reduced under signal conditions, and the efficiency is increased.

Another problem introduced with the use of transformer coupling is the possible introduction of H2 or even-order (second order) harmonic distortion. The d-c current of the transistor collector will be flowing in the primary of the transformer, which sets a flux condition, as shown in figure 4, point A.

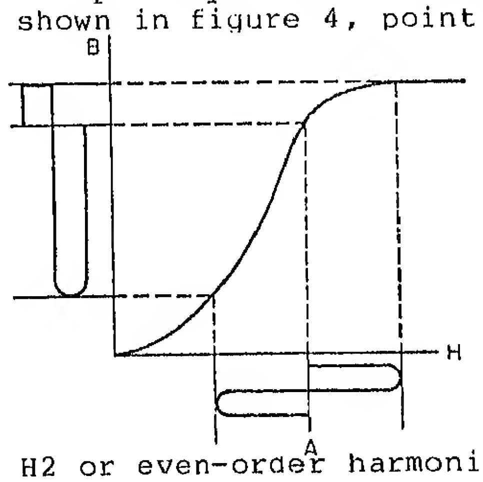


FIGURE 4 - H2 or even-order harmonic distortion.

As signal current is increased, the transformer core approaches saturation. If the amplifier is driven too hard, the core will saturate and cause clipping of the signal, as indicated in figure 4. This is known as H2 distortion.

PARAPHASE AMPLIFIER CIRCUITS

General

Phase-inverter circuits are used to produce an oppositely polarized signal simultaneously with the normal output signal. Thus, two equal and opposite signals are produced for driving push-pull amplifiers. Since the outputs are usually equal in amplitude and opposite in polarity, they are commonly spoken of as being oppositely phased--one signal is always at its minimum when the other signal is at its maximum; therefore, they are out of phase with respect to each other. Any actual change in phase, such as might occur at low frequencies in conventional audio amplifiers, similarly exists in the phase inverter. Because the conventional common amplifier inverts the input signal in the collector circuit, simple single-stage phase inverters can be developed by taking one output from the emitter and the other output from the collector. Another method is to use transformer coupling with a center tap on the transformer secondary.

One-stage phase inverter

Application

The one-stage phase inverter is used to supply two oppositely polarized outputs, from a single-ended input signal, to drive push-pull amplifier stages. It is used in radio receivers, public address systems, and transmitter modulator stages, usually as the driver stage for the power amplifier.

Characteristics

1. The one-stage phase inverter requires more drive than a single-stage amplier.

2. The one-stage phase inverter supplies two outputs with one input signal.

3. The outputs are oppositely polarized and of approximately the same amplitude.

4. The bias and load resistance are selected to provide equal output signals.

5. The one-stage phase inverter provides better frequency response than is possible with an input transformer.

6. The one-stage phase inverter is class A-biased for equal swings; normally, it does not use either class AB or class B operation.

7. The one-stage phase inverter usually uses fixed-bias, but applications of self-bias may be encountered.

Circuit analysis

General

Where a single-ended stage is used to drive a push-pull amplifier, it is necessary to supply the push-pull stage with two input signals of opposite polarity. While a center-tapped transformer may be used, it has been found that RC coupling generally provides better frequency response, more economically, with a reduction in weight and space, by the elimination of the transformer. The unbalanced phase inverter, which uses a load in the emitter and a load in the collector to develop the oppositely polarized outputs, is sometimes referred to in other publicatons as the "split-load circuit." Actually, the load is not split; identical load resistors are used to obtain equal output amplitudes. A balanced output condition may be obtained in the single-stage phase inverter by adding another resistor.

Circuit Operation.

A one-stage unbalanced phase inverter is illustrated in figure 5.

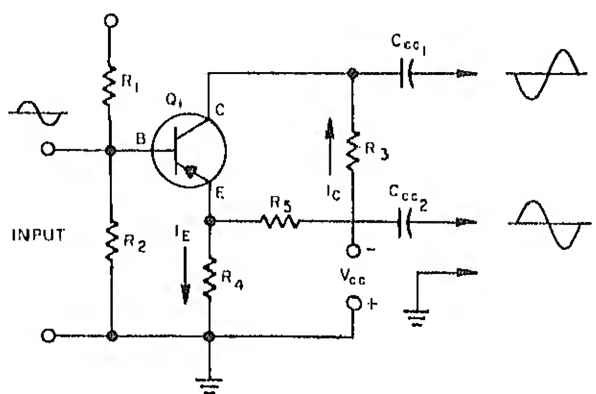


FIGURE 5.--One-stage unbalanced phase inverter.

Fixed voltage-divider bias is supplied by resistors R_1 and R_2. The bias is normally class A, with the transistor operating at the center of its dynamic transfer curve. Thus, equal swings about the bias point (with equal loads) will produce equal output signals. R_3 is the collector load, and R_4 is the emitter load. Both loads are of the same value to produce equal output signals, which are coupled through C_{cc1} and C_{cc2} to the push-pull stage.

When a negative input signal is applied to the base of Q_1, it adds to the forward base of Q_1 and causes the emitter and collector currents to increase. Electron flow is in the direction indicated by the arrows. The emitter current flowing through R_4 produces a negatively polarized signal, while the collector current flowing through R_3 produces a positively polarized signal. Since R_3 and R_4 are identical in value and the collector current is almost equal to the emitter current (less the small amount of base current), equal-amplitude output signals of opposite polarity are produced. On the opposite half cycle of operation, the input signal becomes positive and reduces the forward bias, which reduces both the emitter and collector currents. Assuming that the drive is such that conduction almost stops, the collector output becomes negative and almost equal to the supply voltage. Simultaneously, the emitter current is reduced to nearly zero and the emitter becomes positive with respect to the collector. The emitter and collector outputs change polarity as the input signal changes; the emitter output is in phase and the collector output signal is out of phase with the input signal.

Unfortunately, the collector output impedance is higher than the emitter output impedance, and an unbalanced output condition results. Even though equal amplitude output signals are developed, the push-pull input is basically mismatched for the emitter output and matched for the collector output. As a result, distortion occurs with strong signals. A balanced output is provided by connected R_5 between the emitter and C_{CC2}. The input impedance then becomes high for both push-pull transistors, since the impedance of the emitter is now determined by R_4 and R_5 connected in series and their total value is chosen to provide an impedance equal to R_3. The difference produced by strong signals is thus eliminated. Because the voltage developed across R_5, R_4 will be made larger than R_3 to compensate for the loss in input voltage which will otherwise occur.

Since R_4 is unbypassed, the voltage developed at the emitter is degenerative and in effect opposes the input voltage in essentially the same manner as negative feedback. A larger driving voltage must therefore be applied to the base of the phase inverter than would normally be required for an amplifier without feedback. Where this input drive is limited or unavailable, a two-stage phase inverter is generally used because of its reduced drive requirements.

<u>Two-Stage Phase Inverter</u>

Application

The two-stage phase inverter is used in receivers, public address systems, and modulators to produce sufficient power to drive a high-powered push-pull stage from a single-ended input.

Charateristics

1. Only a small input signal is necessary to drive the stages to full output.

2. The two-stage phase inverter supplies two output signals for a single input signal.

3. The output phases (and polarities) are opposite and suitable for a push-pull input.

4. Operation is usually class A, although class AB or class B applications may be encountered.

5. More than twice the power output of a single-stage phase inverter is obtained.

6. Distortion is equal to or less than that of the single-stage circuit.

Circuit analysis

General. The two-stage phase inverter uses two separate transistors operating at their full capabilities in the common-emitter configuration to provide a larger power output than the one-stage phase-inverter circuit. Since the output is taken from the collector of each stage, there is no negative feedback in the emitter circuit to overcome (as in the single stage), so that less drive than that required for the single-stage phase inverter is required. As a result, more output power is obtained with less drive than for a single stage.

Circuit operation. A typical two-stage PNP transistor phase inverter is shown in figure 6. Transistors Q_1 and Q_2 are basic common-emitter-connected amplifiers, each supplying a single output. Q_2 is connected in cascade with Q_1 but has R_5 connected in series with the base to limit the current and reduce the driving signal to a value equal to that applied to Q_1. With the input signal to Q_2 held to the same value as the input to Q_1 the output of Q_2 is made to equal the output of Q_1. Since the CE circuit produces an inverted output polarity, the two separate output signals are equal in amplitude but opposite in polarity, making them suitable for driving a push-pull stage. Fixed class A bias is provided for both stages through voltage divider resistors; R_1 and R_2 bias Q_1, while R_6 and R_7 bias Q_2.

Resistors R_4 and R_9 are emitter-swamping resistors, used for thermal stabilization, and are bypassed by C_1 and C_2 to prevent degeneration. Since the capacitors bypass any a-c component of the signal, they are affected only by d-c current variations produced by changing temperature. When a temperature change increases the emitter current, it produces a d-c voltage across the swamping resistors which opposes the operating bias and automatically reduces the emitter current to compensate for the increase. Resistors R_3 and R_8 are the collector loads of Q_1 and Q_2, respectively, across which the output voltage is developed. The collector of Q_1 is RC coupled to the base of Q_2 by R_5 and C_{CC_1}, and the push-pull outputs are coupled through capacitors C_{CC_2} and C_{CC_3}.

When a negative input signal is applied to the base of Q_1, the forward bias is increased and the emitter and collector currents are increased above the resting (or quiescent) value. Electron flow is from the emitter through C_1 to ground, and from the collector supply through R_3 to the collector. As shown in figure 6, the collector output of Q_1 is positive and is coupled through C_{CC_1} to the base of Q_2 and through limiting resistor R_5 to drive Q_2. (The inverted output from the collector of Q_1 is supplied to the push-pull circuit by C_{CC_2}.) The value of R_5 (may be variable) is chosen to supply an input to Q_2 just equal to the amplitude of the input signal applied to Q_1. With a positive signal applied to the base of Q_2, the forward bias is reduced and the emitter and collector currents of Q_2 are reduced. Electron flow is from the emitter of Q_2 through C_2 to ground, and from the collector supply through R_8 to the collector. Since class A bias is used, and assuming that the base voltage applied to Q_2 is just equal to the bias, collector current flow is reduced to zero and the collector voltage rises to that of the negative supply (both ends of R_8 are negative with respect to ground). Thus, a negative output is obtained from the collector of Q_2 and is applied through C_{CC_3} as the oppositely polarized (in-phase) push-pull driving signal. Since Q_2 operated practically instantaneously (there is no inherent delay), the two outputs appear on the push-pull grids simultaneously. (Note that passage through one stage inverts the signal, while passage through two CE stages returns the signal to the original polarity.)

Assuming a sine wave input, when the negative half-cycle is completed, the signal reverses and a positive input is now applied to the base of Q_1. The positive input reduces the forward bias of Q_1 to zero (assuming full swing), and the collector voltage rises to that of the negative supply, which produces a negative output. The large amplitude collector output is dropped through R_5 so that it is approximately equal to the input signal amplitude applied to Q_1. This small negative input to the base of Q_2 increases the forward bias and causes

the collector current flow through R_8 to increase. Electron flow is from the supply through R_8 to the collector, which produces a positive voltage drop at the collector (the polarity of this voltage drop is opposite that of the previous half cycle), so that the output from Q_2 is now positive. Since there is no inherent delay in the operation of the transistor, the positive output from Q_2 and the negative output from Q_1 appear practically simultaneously at the push-pull inputs.

Limiting resistor R_5 acts as a balancing resistor to equalize the output of both stages. The transistors need only be of similar types, matched pairs are not required. The collector resistors are usually made equal so that identical currents will produce equal output voltages. Where little power is required, such as that needed to drive a conventional class A push-pull stage, swamping resistors R_4 and R_9 and their associated bypass capacitors C_1 and C_2 may be eliminated from the circuit, and the emitters may be connected directly to ground. In applications where distortion becomes critical, the use of feedback from the collector is resorted to by connecting bias resistors R_1 and R_6 to their collectors. In figure 6, resistors R_2 and R_7 could be eliminated by changing the values of both R_1 and R_6. It is evident that the basic schematic may vary slightly, according to individual design, using different bias and stabilization methods; however, the operation will be essentially the same, since two stages of amplification are used to invert one of the outputs and thus provide a push-pull output.

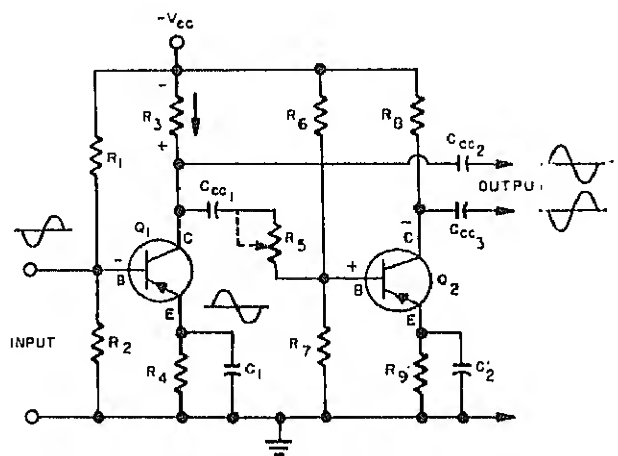


FIGURE 6 - Two-stage phase inverter.

<u>Transistorized push-pull, audio power amplifiers</u>

Audio power (class A, AB, and B) push-pull, transformer-coupled amplifier

Application. The transistor push-pull transformer-coupled audio amplifier is used where high-power output and good fidelity are required; for example, receiver output stages, public address amplifiers, and AM modulators.

Characteristics

1. Collector efficiency is high with moderate power gain.

2. The transistor push-pull transformer coupled audio amplifier requires twice the drive of a single transistor stage.

3. Power output is more than twice that of single-transistor stage.

4. Second and higher even-order harmonic distortion is cancelled.

5. Distortion varies with the class of operation; it is least for class A operation, and greatest for class B operation.

6. Collector efficiency varies with the class of amplifier, from 50 percent maximum in class A to 78.5 percent maximum in class B, with an intermediate value for class AB.

7. Fixed bias is usually used, but self-bias may be encounterd in some class A applications.

8. Operates as a large-signal amplifier for all except very small inputs.

9. Emitter swamping is used for thermal stabilization.

Circuit analysis

General. The push-pull transformer-coupled transitor amplifier is similar in a general sense to the push-pull transformer-coupled electron-tube audio amplifier. In the common (grounded) emitter circuit the base of the transistor is equivalent to the electron-tube grid, the emitter equivalent to the cathode, and the collector equivalent to the tube plate. Push-pull amplifiers can be operated class A, class AB, or class B, as determined by the amount of forward bias. The least amount of distortion and power output is produced in class A operation, and the greatest amount of distortion and power output is obtained in class B operation. Class AB stages operate between these levels of distortion and power output. For a given equipment and type of transistor, selection of the operating bias, distortion, and power output is a design problem. Although the different types of operation are similar, there are significant differences among them.

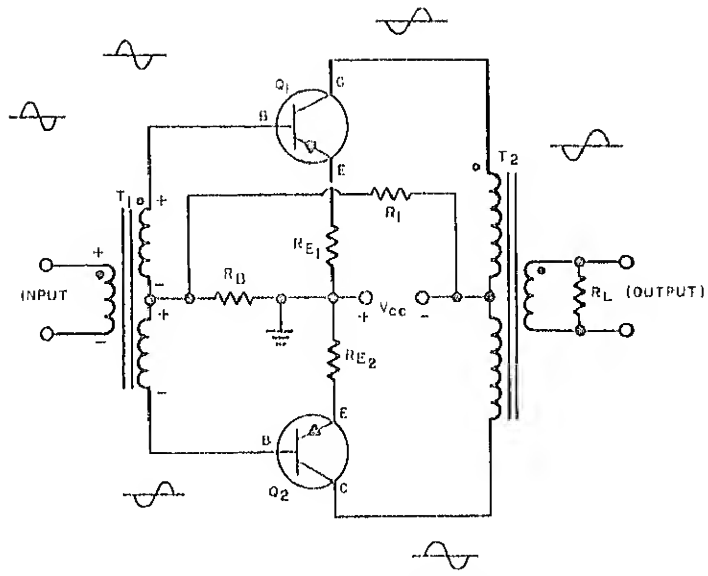
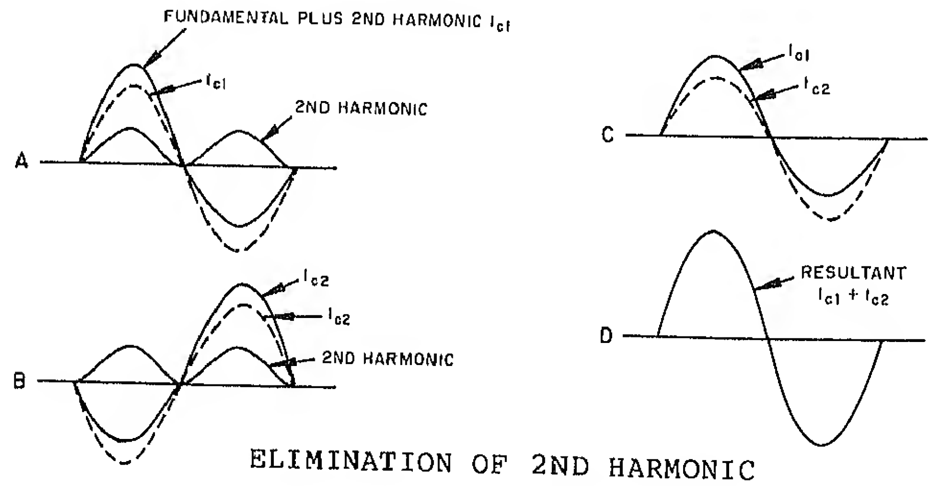


FIGURE 7 - Push-pull transformer-coupled transistor power amplifier.

Circuit operation. Figure 7 shows a PNP push-pull, transformer-coupled output stage. The load resistance may be a loudspeaker, an RF stage, or other type of load. The load is considered to be resistive unless stated otherwise in the text. The input signal is applied to the base of both transistors through transformer T_1. Note that when the top end of the secondary of T_1 is positive, the bottom end is negative. Thus, equal and oppositely polarized signals are applied to the base of transistors Q_1 and Q_2 when an input signal appears in the primary of T_1. The input signal is obtained from a preceding driver power amplifier stage. Very little power is required for class A operation; increasingly more drive power is required for class AB and class B operation. The actual amount of drive power needed depends upon the circuit design and the transistors used; it is on the order of 2 or 3 percent of the output. Transformer input coupling is used to provide maximum drive power and proper matching of the driver stage. Fixed bias from the collector supply is applied through voltage-divider resistors R_1 and R_B. Resistors R_{E_1} and R_{E_2} are the emitter stabilizing resistors, which are left unbypassed to provide a slight amount of degeneration. The collector load consists of the primary resistance of output transformer T_2 plus the resistance reflected from the load connected across the secondary.

Class A operation. With no input signal, the stage is resting in its quiescent condition, drawing heavy collector current and operating at the point of lowest efficiency. Since no change in collector current occurs, no output voltage is induced in the secondary of T_2. Assuming a positive input swing on the base of Q_1 and an inphase connection of T_1, the positive voltage

of the signal subtracts from the normal forward (negative) bias, effectively reducing the base bias and causing less collector current to flow in Q_1. As the collector current is reduced, the changing lines of magnetic flux between the primary and secondary of T_2 induce a voltage in the secondary. At the peak of the input signal, the collector current of Q_1 is reduced to a small value, and the collector voltage approaches the supply voltages (reaches its most negative value). Thus, the common-emitter circuit makes the polarity of the output signal opposite that of the input signal. Simultaneously, the input signal in T_1 is applied as a negative voltage swing to the base of Q_2 (the ends of the secondary winding are oppositely polarized when a voltage is induced), which adds to the forward bias of Q_2. The increase in forward bias causes an increase in the collector current through the primary of T_2, and induces an inphase voltage in the secondary of the output load. The net result of the input signal is to decrease the signal output of Q_1 and to increase the output of Q_2. These induced output voltages are combined in the secondary of T_2 to produce the effect of a collector current equivalent to twice that of a single transistor. Note that the collector current flows in opposite directions through the two halves of the primary of T_1, so that any inphase primary-induced voltage components are cancelled out (second and all even harmonics). The output voltage induced in the secondary consists of the fundamental component and any odd harmonics. The manner in which the second-harmonic component is cancelled out in the secondary is shown in figure 8. In part A of the figure, the positive signal is enhanced by the second harmonic, while the negative



ELIMINATION OF 2ND HARMONIC

FIGURE 8

signal is reduced. In part B, the opposite action is shown for the second half-cycle of operation. The separate resultant

waveforms are shown in part C. In part D, they are combined to form a complete amplified signal with no second-harmonic content. For class A operation, maximum output efficiency and the least d-c dissipation are obtained with maximum signal swing. To make certain that the power dissipation ratings of the transistor are not exceeded, only half the maximum permissible collecstor voltage is applied, since the applied voltage tends to double because of the inductive effect of the transformer. For class A operation, the transistor is biased and operated at the center of the forward-transformer-characteristic curve, so that equal base-current swings will produce approximately equal collector-current swings. The transistor thus functions as a large-signal amplifier. Since a large-signal amplifier operates over a much greater range of current and voltage than a small-signal amplifier, circuit design is accomplished graphically, using the actual transistor currents to determine the range over which minimum distortion and maximum power output can be obtained. Since much heat is dissipated at the collector for large power outputs , the shell of the power transistor is usually connected firmly to the chassis for direct conduction and reduction of heat. (The chassis acts as a heat sink.) Where the shell must be insulated from the chassis, it is usually separated by a thin wafer of mica (or other suitable material) to provide insulation and yet allow full heat transfer. Where minimum distortion is required, the transistors are selected in matching pairs. Because of the high-power-handling capability required for class A operation, transistors are usually operated class B or class AB.

Class B operation. In true class B operation, the bias is such that no collector current flows for one half of the cycle. Thus, each transistor reproduces only half of the cycle, and two transistors are required to reproduce any signal faithfully (an exception is the class B RF amplifier, which uses a tank circuit and amplifies only a single frequency). Since at cutoff a reverse current flows in the transistor, collector current is never completely cut off, and a small quiescent current flows during the inactive half-cycles of transistor operation. (This quiescent reverse current should not be confused with the small forward current which flows in class AB operation because the bias is not at cutoff.)

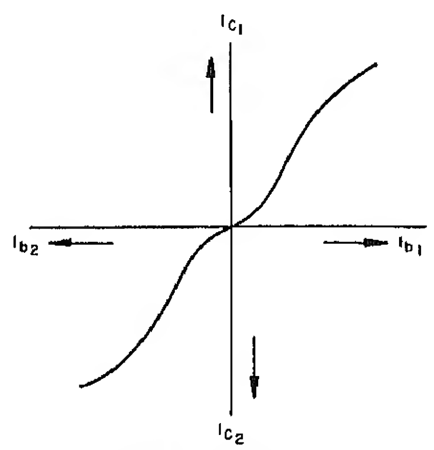


FIGURE 9- Compasite current transfer characteristic, class B operation.

For two transistors completely biased off, the forward transfer characteristic is as shown in figure 9. The two transfer curves are placed back-to-back to make the complete dynamic operating curve. Note how this curve is rounded off at the beginning and at the end instead of being a straight line. This is typical of the non-linearity obtainable at cutoff and illustrates why class B operation produces the greatest distortion. The accompanying circuit is that of a typical class B stage operated with zero bias, shown in figure 10. Emitter swamping resistors R_1 and R_2 are used for thermal compensation and unbypassed to provide a slight amount of degeneration. Note here one of the differences between the electron tube and the transistor. At zero bias, the conventional electron tube conducts

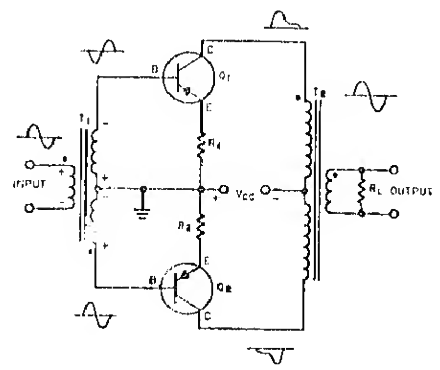


FIGURE 10 - Class B push-pull stage.

heavily, and it is necessary to apply considerable negative bias to achieve class B operation. On the other hand, the transistor always has the collector reverse-biased, thus, in the absence of a forward base bias (that is, at zero bias), no collector current can flow. When a signal is to input transformer T_1, a voltage is applied to the base of transistor Q_1 and an oppositely polarized voltage is applied to the base of Q_2 (the polarity for the initial half-cycle is shown on the schematic). When the input signal is applied, the flow of current in the primary of T_1 induces an oppositely polarized signal on the base of Q_1 (transformer connected out-of-phase). Thus, the positively swinging input appears as a negative (forward) bias on the base of Q_1, which causes collector current to flow in the top half of the primary of T_2 and induces an output voltage in the secondary. At the same time, the input voltage applied to Q_2 cut off. During the entire half cycle, Q_1 conducts while Q_2 remains cut off. When the input signal reverses polarity,

reverse bias is applied to cut off Q_1's collector current, and forward bias is applied to Q_2. Consequently, Q_2 conducts and the increasing collector current through the bottom half of the primary of T_2 induces a voltage in the secondary of the output transformer. During this half-cycle, Q_1 remains cut off while Q_2 conducts. Thus, Q_1 and Q_2 alternately conduct when the input signal produces a forward bias. Since the outputs of Q_1 and Q_2 are combined in the secondary of the output transformer, the input signal is reproduced in amplified form, but of opposite polarity. If the output transformer is connected in phase, the same polarity of output exists as in the primary. When it is connected out of phase, the opposite polarity exists. Since there is no heavy flow of quiescent (when no signal is applied) current, maximum dissipation occurs during the signal (at about 40 percent maximum collector current), and less heat is developed for the same signal as in a class A amplifier. Hence, the transistor can be driven harder to obtain greater efficiency and more power output than is obtained in the class A stage., Emitter swamping resistors R_1 and R_2 provide a small opposing bias voltage to prevent thermal runaway. They are not bypassed with capacitors as in class A operation, because the capacitors would charge during the operative half cycle and discharge during the inoperative half cycle, which would cause a change in bias. Because of the large peak current which flows through these resistors, they are kept to a very low value of resistance to prevent excessive degeneration and loss of amplification. In some applications, by proper selection of transistor types and good design, they are not needed. When used, their main function is to provide thermal stabilizatin, and any beneficial degeneration which may occur from their use is only a secondary consideration. Otherwise, they have no effect on the operation of the circuit, since the transistors operate alternately in class B operation. There is an increase in third-harmonic distortion produced when the waveform passes through zero (this is known as crossover distortion). The development of this type of distortion is shown by projecting a sine-wave-input signal on the transfer-characteristic curve, as shown in figure 11. The distortion is greatest for small input signals and least for large input signals. This distortion is eliminated by applying a small forward bias to the base-emitter junction of the transistors.

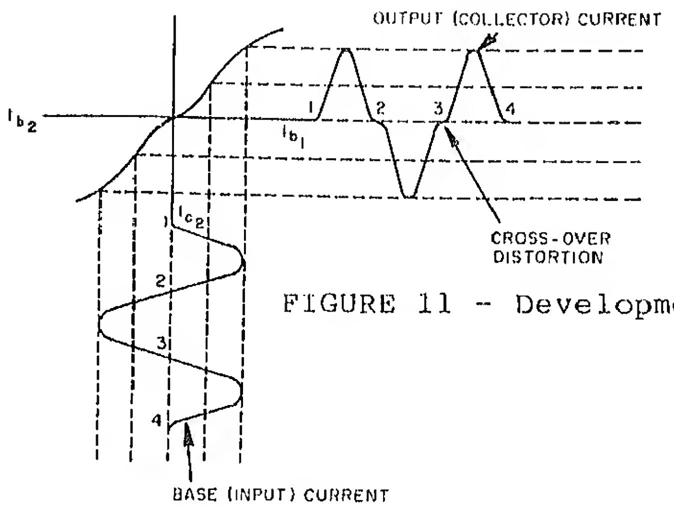


FIGURE 11 - Development of crossover distortion.

Class B operation is used only when the large amount of third-harmonic distortion can be tolerated.

Class AB operation. The schematic of a class AB amplifier is basically identical with that of the class A amplifier. The only difference is the bias voltage-divider resistors R_1 and R_B are of different values. Only a slight forward bias is applied, and only a small collector current flows with no signal applied. While this current is essentially wasted, it does eliminate the crossover distortion which would be produced if the forward bias were reduced to zero. It is evident that class AB operation produces slightly less output than class B operation. Because of the small resting current, the transistor can be driven harder than the class A stage; consequently, greater output can be obtained than for class A operation. The efficiency averages about 65 percent for a well-designed class AB stage. The small resting current, like the average current drawn in class A operation, cancels out the flux in the primary of the output transformer (each side flows in a different direction), and there is no output produced until a signal is applied. When the input signal is applied, Q_1 conducts and Q_2 is driven to zero conduction on one half cycle, while on the other half cycle, Q_2 conducts and Q_1 is driven to zero. The resultant signal swings are unequal and considerable second-harmonic distortion is produced in the primary of the output transformer; however, it is cancelled out in the secondary when both signals are combined (assuming that the transistors are fairly well matched). Thus, only fundamental and third-harmonic distortion can exist in the output. This form of operation is identical with class A operation, except that more odd-harmonic distortion is produced because the transistors operate for less than 360° of the cycle.

Figure 12 shows the composite transfer characteristic for a typical class AB stage. When compared with the transfer curve for the class B stage shown previously, it is evident that the operation is more linear except for very large signal swings. Projection of the input signal on the composite transfer curve shows the collector output,

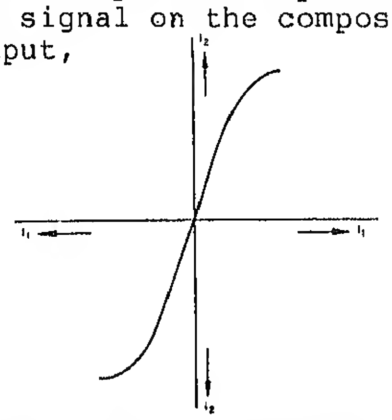


FIGURE 12 - Composite current transfer characteristic, class AB operation.

which, when compared with that of class B stage shown previously, indicates the improvement in fidelity obtained with class AB operation and the total elimination of crossover distortion, as shown in figure 13.

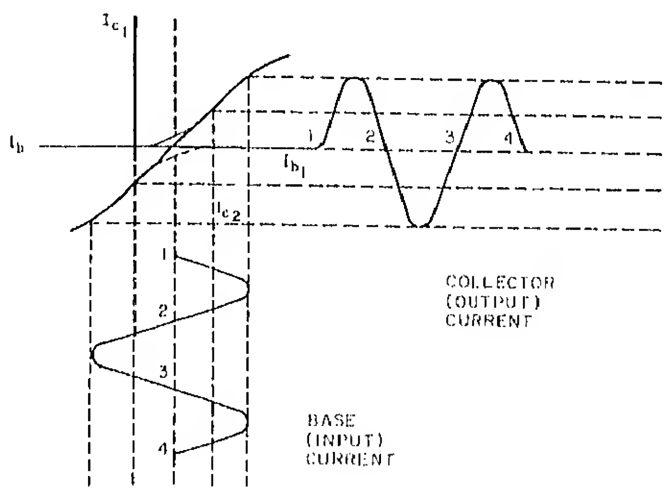


FIGURE 13 - Development of class AB signal.

Audio power amplifier, push-pull, single-ended complementary circuit.

Application. The push-pull, single-ended complementary audio amplifier is used where high power output and fidelity are required; for example, in receiver output stages, in public address amplifiers, and in AM modulators, where reduced weight and space are prime requirements.

Characteristics

1. Collector efficiency is high with moderate power gain.

2. The single-ended complementary audio amplifier requires only half the drive of the conventional push-pull amplifier.

3. Power output is twice that of a single transistor stage.

4. No input or output transformer is used.

5. Distortion varies with the class of operation.

6. Usually is biased class B, but may be biased class A in some applications.

7. Fixed bias is usually used, but self-bias may be encountered in some applications.

Circuit analysis

General. Complementary symmetry is unique with transistors and has no electron-tube counterpart. Recall from basic theory that a transistor may be either the PNP or NPN type and that the bias and polarities are opposite.

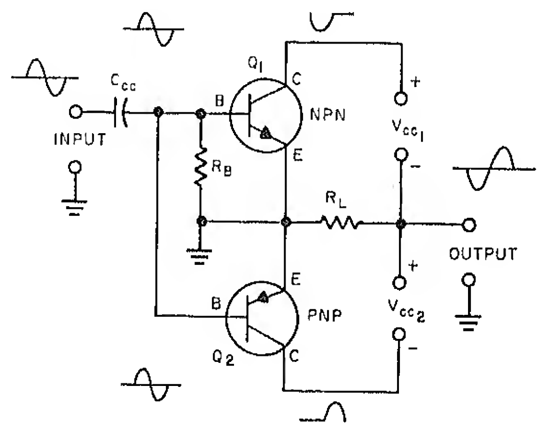


FIGURE 14 - Zero bias complementary-symmetry push-pull circuit.

Two different types of transistors may be used back-to-back to provide push-pull operation without the necessity for phase-inverting input and output transformers. An economic advantage is gained in that the cost of the transformers is eliminated; and a more uniform response is obtained, since the reactive effects of the transformers are also removed from the circuit.

Circuit operation. Figure 14 shows a typical single-ended push-pull complementary-symmetry circuit. The operation is class B at zero bias.

Resistance-capacitance input coupling is used, with C_{cc} acting as the coupling capacitor and R_B as the base return resistance across which the input signal is applied. With both emitters grounded and no bias applied, the bases of the transistors are zero-biased at cutoff. No current flows in the absence of an input signal. When an input is applied, both bases swing in the same direction. Since Q_1 is an NPN transistor,

the positive-going input signal produces a forward bias. Q_2 is a PNP transistor and requires a negative potential for forward bias, the input signal has no effect other than to reverse-bias Q_2 and hold Q_2 in a cutoff condition. Thus, during the positive half of the input signal, only Q_1 conducts. During the negative portion of the input signal, Q_1 is biased off beyond cutoff by a reverse bias, and a forward bias is applied to Q_2 causing collector current to flow for the entire negative half cycle. Thus, each transistor conducts alternately for half of the cycle, and two transistors are required to reproduce the input signal. Note that the bases are connected in parallel and since only one transistor operates at a time, only enough drive for a single stage is required instead of twice the drive as in normal push-pull operation. Because the transistors are of opposite types, two equal-voltage collector power supplies are required, one negatively polarized and the other positively polarized. (A single supply can be used with proper circuit changes, but twice the collector voltage of a single stage is required.) The load resistor, R_L (which may be the voice coil of a loudspeaker), is connected from the common connection between the power supplies and the emitters. In this instance, the emitter end is grounded, so that the power supplies are actually floating above ground. When the input signal is applied and develops an output for each half-cycle, the output is added together in the common load and no transformer is required. To develop maximum power, a low impedance is needed. Otherwise, if high-impedance loads are used, an output transformer will be required for proper load matching. In this instance, however, the winding need not be center-tapped, since the output is single-ended. Because the output is single-ended (taken between the collector and ground), the collector load is calculated on the basis of the full primary-to-secondary turns ratio--not on one-half of the primary-to-secondary turns ratio, as in the conventional push-pull stage. Thus, the loading is one-fourth of the normal push-pull output, which accounts for the low-impedance output. In transistor circuits, it is necessary to separate the d-c component in the output from the a-c component by the capacitive or transformer coupling (except in the special case of the d-c amplifier). In the complementary arrangement, such provisions are unnecessary. Both d-c power supplies are connected in series with the transistors, and only one transistor is operative at a time. There is no net flow of d-c around the circuit. When Q_1 conducts, there is a flow of current through R_L, the transistor, and the power supply in one direction. When Q_2 conducts, the flow is through R_L. Q_2, and the power supply in the opposite direction. There is no circulating current, and the d-c is effectively removed from the load circuit, since only the continuously varying a-c component

flows through the load. Likewise, in the base circuit, there is no continuous flow of d-c, since the current flows out of the base when Q_{2E} conducts and into the base when Q_1 conducts. The charging and discharging of the coupling capacitor and its possible effect on changing the base bias are therefore of no consequence in this circuit.

In the preceding discussion, it has been assumed that the transistors were balanced (or matched), having identical gain and collector currents. Like the conventional push-pull amplifier, this matching is necessary to obtain maximum output with minimum distortion. The complementary-symmetry circuit has identical collector currents, since the transistors are series-connected and the biasing is adjusted to equalize the collector voltages. In the case of class A or AB operation, the bias point in the base circuit is affected by drive and base current drain: keeping the signal from affecting the bias is one of the important design problems. So far as the technician is concerned, the practical effect is that with better design, less distortion is obtained, with a maximum of amplification. While the common-emitter circuit is used in most transistor amplifiers, better performance is obtained from improved. The collector supply can be grounded instead of floating (which reduces power supply ripple), and the effect of negative feedback is obtained, which requires less balance between transistors and improves fidelity asnd response characteristics. Both circuits are identical except that the ground is removed from the emitters and placed on the common power supply connection, as shown in figure 15.

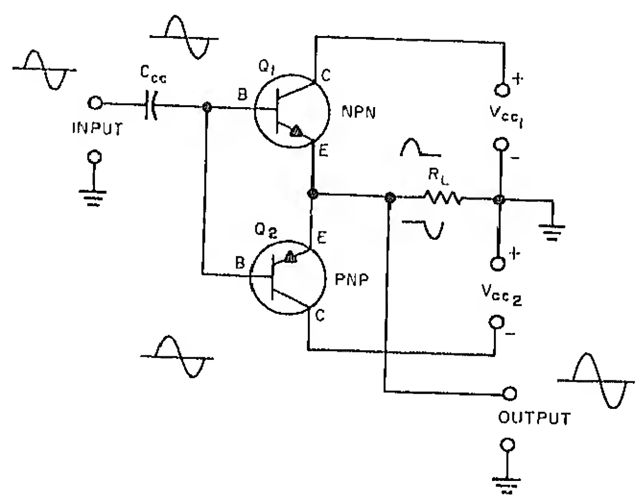


FIGURE 15 - Common (grounded)-collector complementary-symmetry push-pull circuit.

As in other common-collector circuits, no polarity inversion of the output signal occurs, so that the inputs and outputs are of the same polarity. In operation, the circuit functions in the same manner as the common-emitter push-pull complementary-symmetry amplifier previously described. Only one transistor operates at a time, zero bias is employed, and the output is taken from the emitters to ground. Collector current flows through Q_1, power supply V_{CC_1} and load resistor R_L in one direction, and through V_{CC_2}, Q_2, abd R_L in the opposite direction, as the transistors are alternately forward-biased by the input signal. There is one difference, however, in that more input (drive) voltage is required to obtain full output because of the degenerative effect of connecting the load between the emitters and ground. Figure 16 shows the complementary-symmetry push-pull circuit connected for use with a

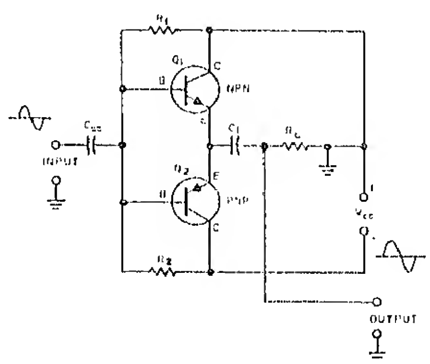


FIGURE 16 - Complementary-symmetry push-pull amplifier with common power supply.

single power supply and with feedback from collector to base. Connecting capacitor C_1 in series with load resistor R_L permits the use of a single power supply. Since no d-c normally flows through the load, the insertion of the blocking capacitor has no effect on either a-c or d-c operation. Since both transistors are connected in series with the power supply, twice the d-c voltage of one supply is necessary. In addition, resistors R_1 and R_2 are employed to provide a fixed base and a slight amount of feedback from collector to base. The feedback reduces the matching requirements, and the d-c bias is adjusted by selecting the values of R_1 and R_2 so that equal collector voltages are obtained. (With the series connection of transistors, the same value of current flows throughout the circuit.) As far as dynamic operation is concerned, it is also identical with that of the previously discussed common-emitter complementary-symmetry circuit. When a forward bias is applied by the signal, the transistor conducts. With a sine-wave input signal applied, a sine wave of current flows (at audio frequencies) through capacitor C_1 and load R_L to develop the output signal.

NOTETAKING SHEET 3.4.1N

AUDIO-FREQUENCY POWER AMPLIFIERS

REFERENCES

1. Basic Electronics, Vol. I. NAVPERS 10087-C. Chapter 13.

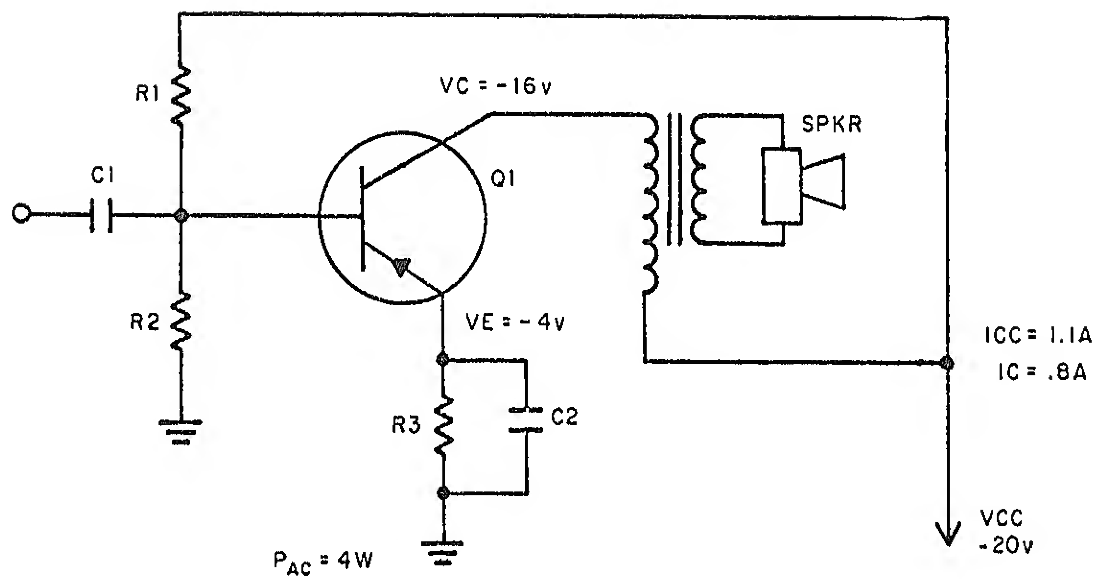
2. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 5.

3. Shrader, Robert. Electronic Communication. Fourth Edition. N.Y.: McGraw-Hill Company, 1980. Pages 296 to 301.

NOTETAKING OUTLINE:

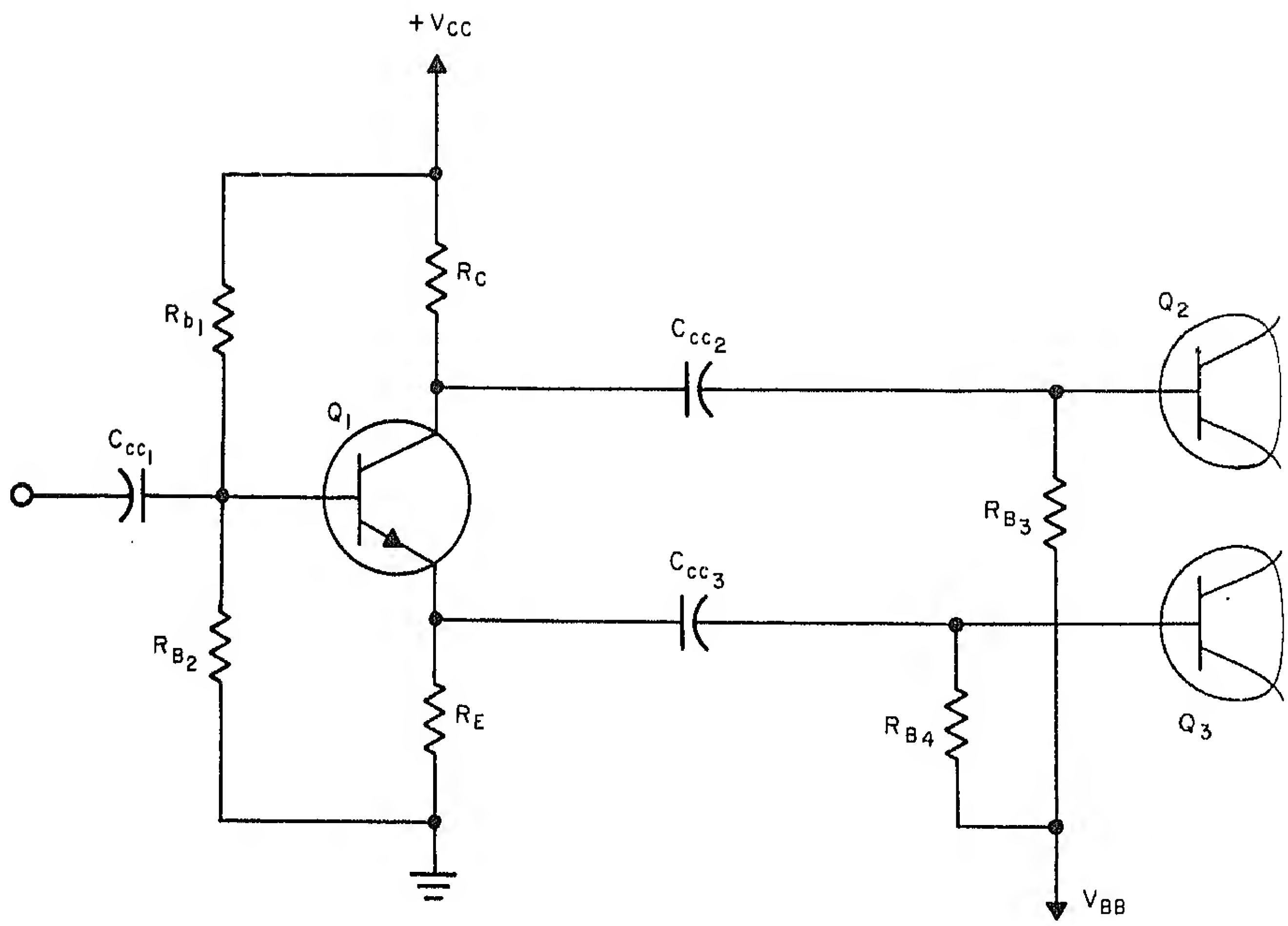
A. General Considerations

B. Single-ended Class A Power Amplifier

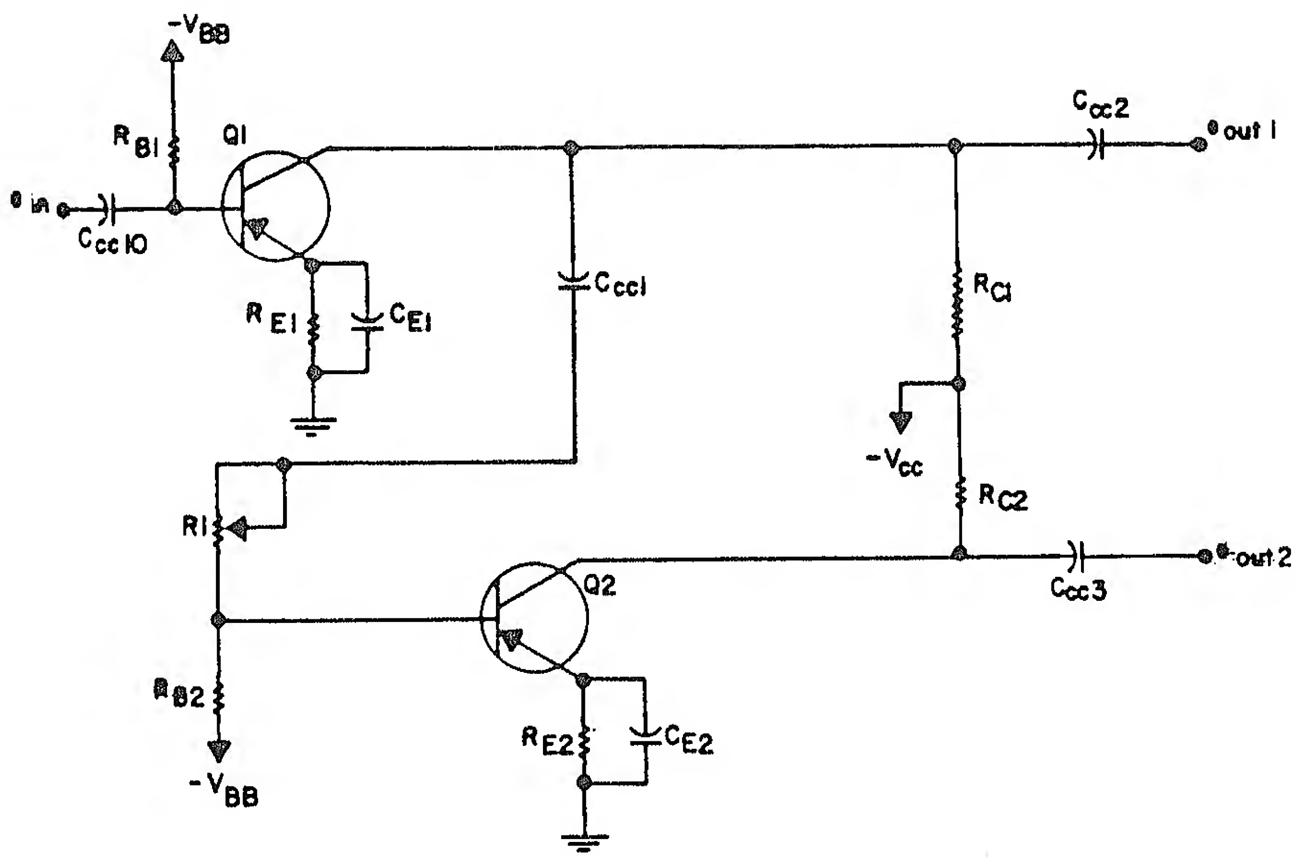


Single-Ended Amplifier

C. Paraphase Amplifiers

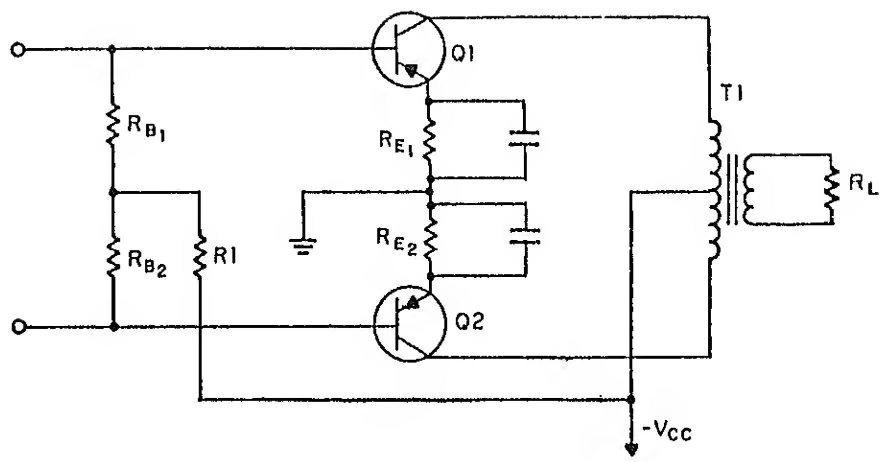


Single-Stage Split-Load Phase Splitter

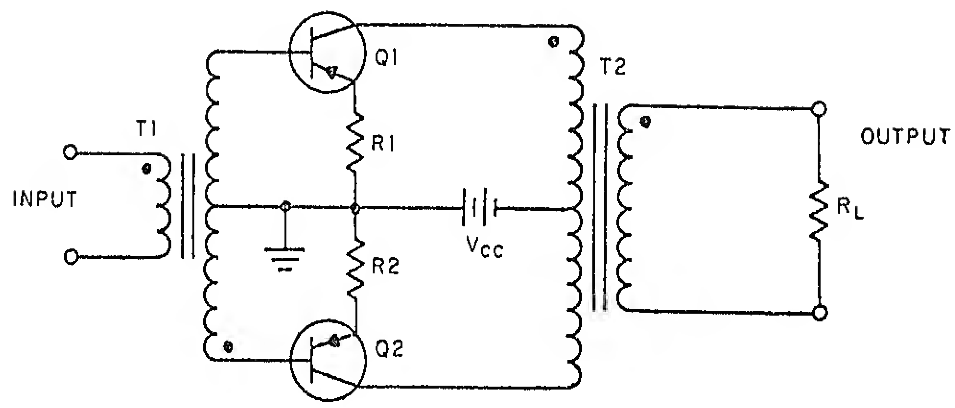


Two-Stage Paraphase Amplifier

D. Push-pull Power Amplifiers

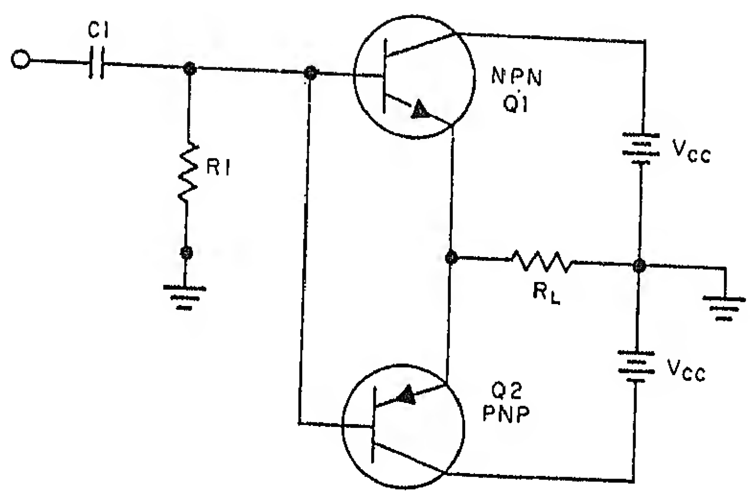


Class A Push-Pull



Class B Push-Pull Stage

E. Complementary-symmetry Circuits



Push-Pull Single-Ended Complementary Symmetry

INFORMATION SHEET 3.5.1I

RC OSCILLATORS

INTRODUCTION

Without the electronic oscillator, very few advanced electronic circuit applications would be possible. The importance of a thorough understanding of oscillator theory and operation cannot be overemphasized. The list of equipment employing oscillators includes RADAR, SONAR, guided missiles, communications gear, test equipment, etc. RC oscillators produce a sinusoidal output without the use of an LC resonant tank circuit. Complete coverage of every type of oscillator is impractical, but an understanding of the basic oscillators will provide the foundation for working with new circuits or other oscillators.

REFERENCES

1. Basic Electronics, Vol. I, NAVPERS 10087C. Chapter 15, pages 295 to 337.

2. Basic Theory and Application of Transistors. NAVWEPS 00-80T-86, TM 11-690. Pages 165 to 180.

3. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 6, pages 6-1 to 6-48, 6-61 to 6-67 and 6-94 to 6-101.

4. Maintenance Handbook, Device 11D13A. NAVTRADEV P-2974-I and II. Dec. 1965. Pages 3-17, 3-18, and 7-43.

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INFORMATION

General. It is not necessary for an oscillator to employ a resonant circuit; any circuit that provides the necessary regenerative feed-back between collector and base (or emitter) can be made to oscillate.

RC Phase-Shift Oscillator

The arrangement shown in figure 1, commonly termed an "RC phase-shift oscillator," will oscillate at some frequency that causes the resistance-capacitance (RC) network to shift the signal frequency reaching the collector by 180°

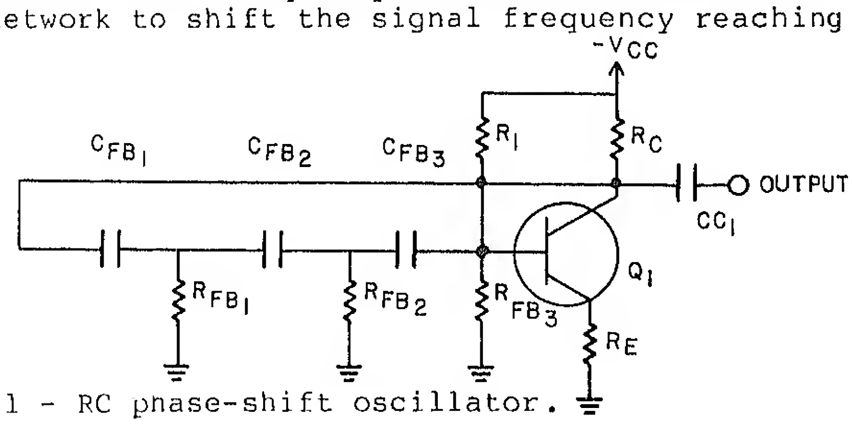


FIGURE 1 - RC phase-shift oscillator.

Any signal on the base of the transistor Q_1 will be amplified and inverted in the collector. This provides the first 180° of phase shift. The feedback network, composed of three RC networks connected together, provides the other 180° of phase shift. This means that the signal being returned to the base of the transistor Q_1 is in phase with the beginning signal. The gain of the transistor must be sufficiently high to overcome the attenuation of the resistance coupled networks.

With any phase-shift oscillator, a minimum of three RC networks are used. Each network causes a 60° phase shift. More than three RC networks can be used, and the phase shift of each network will be less. When all the networks are alike ($C_{EB_1} = C_{FB_2} = C_{EB_3}$ and $R_{FB_1} = R_{FB_2} = R_{FB_3}$), the circuit will oscillate at some particular frequency determined by the relationship of the resistance-capacitance networks. All other signal frequencies appearing at the base of transistor Q_1 will be shifted other than 60° by each network, which will cause them to become attenuated at the base of Q_1.

The transistor in the RC phase-shift oscillator is normally biased to operate class A. This is accomplished by a d-c voltage divider, composed of R_1 and R_{FB_3} in the base of transistor Q_1. As the circuit begins to oscillate, we find that the regenerative feedback causes the transistor to operate at or near saturation. The emitter resistor R_E can be left unbypassed to provide some degenerative feedback. This will improve the frequency stability of the circuit. Circuit operation can be further improved by putting a large resistance from the collector of Q_1 to the base. This provides the circuit with more degenerative feedback, which will further improve the stability of the circuit and sine wave quality out of the phase-shift oscillator. Care must be taken to avoid a feedback of too much degeneration, as oscillations will stop.

As with most oscillators, circuit operation is started by random noise and circuit variations when power is first applied. Noise contains a broad spectrum of frequencies, and any noise present on the base of Q_1 will be amplified and inverted in the collector. All signal frequencies present on the collector will be fed back to the base of Q_1 by the three RC networks, but only the signal that arrives at the base in phase with the original will be strongly reamplified and will maintain oscillations.

Wien-bridge oscillator

There are several RC oscillators in which the necessary phase reversal is obtained by the use of a two-stage RC-coupled amplifier. One such oscillator, the Wien-bridge, uses feedback from the collector of the second stage to the base of the first stage to sustain oscillations. Another type of RC oscillator, the Twin-T, uses regenerative feedback from the emitter of the second stage to the emitter of the first stage to sustain oscillations.

The Wien-bridge oscillator is widely used in test equipment, radio transmitters, and other equipment that operates in the 30-kHz range and below. The Wien-bridge oscillator is also used in the audio-frequency range, where size of inductance in conventional oscillators becomes very large and prohibitive.

The Wien-bridge oscillator, shown in figure 2, will oscillate at such a frequency that the input voltage to the bridge circuit, fed back via capacitor C4 from point B to ground and point A to ground, is in phase.

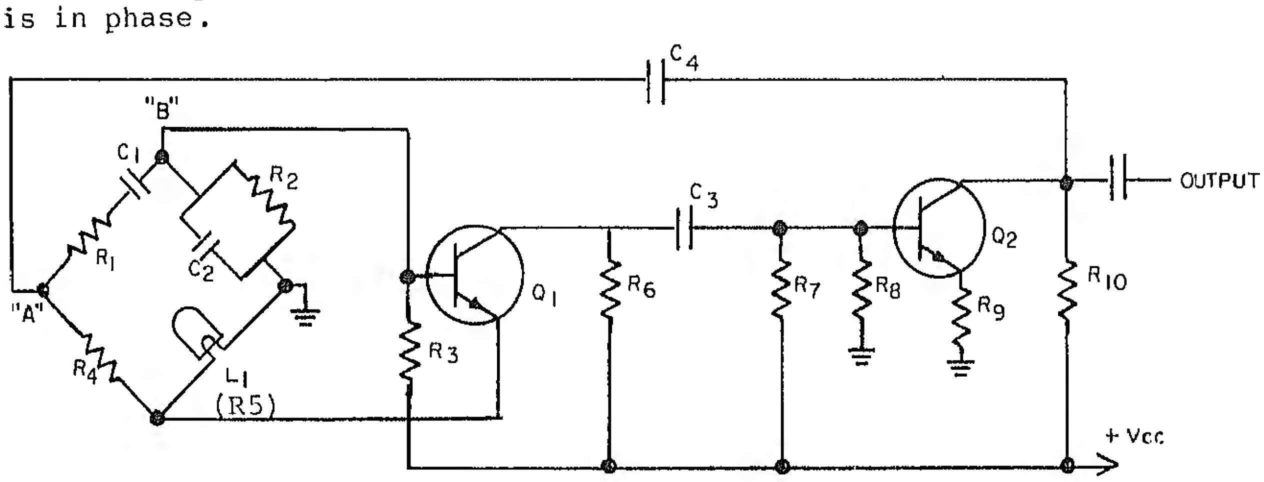


FIGURE 2 - Wien-bridge oscillator.

Transistor Q_1 is the oscillator, and transistor Q_2 acts as an amplifier inverter. Thus, even without the bridge circuit, composed of R_1, R_2, R_4, and R_5, C_1 and C_2, this circuit would oscillate, since any signal that appears at the base of Q_1 is amplified and inverted by both Q_1 and Q_2. Any signal voltage fed back to the base of Q_1 must reinforce the initial signal, which causes oscillations to be set up and maintained. This system however would amplify voltages of a very wide range of frequencies: voltages of any frequency or of any combination of frequencies can cause oscillations. The bridge circuit is then used to eliminate feedback signal voltages of all frequencies, except the frequency desired in the output.

Figure 3 is electrically the same circuit as figure 2; however it is easier to follow the feedback paths.

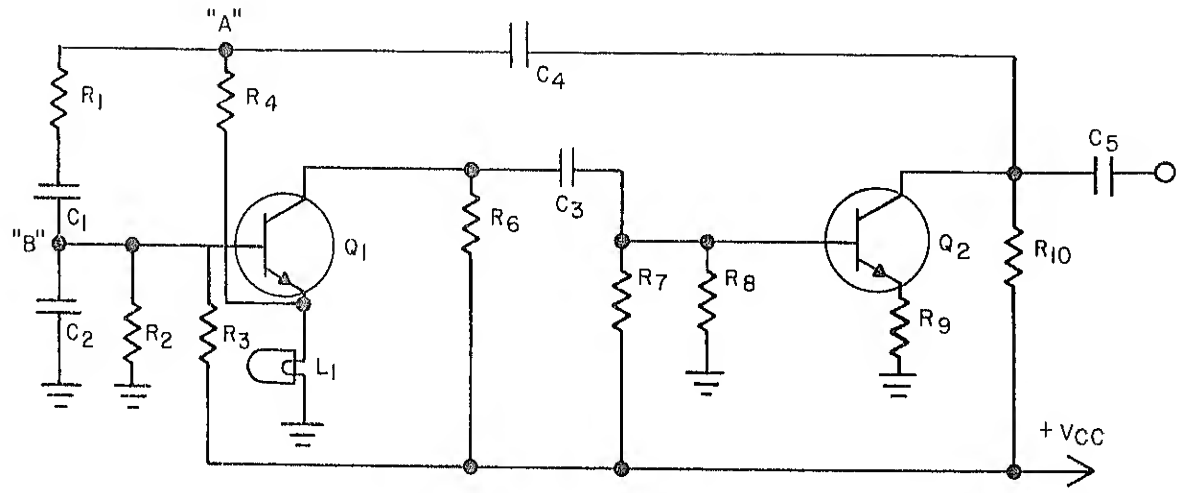


FIGURE 3 - Wien-bridge oscillator.

The bridge allows a voltage of only one frequency to be effective in the circuit because of the degeneration and selective filtering in the regenerative feedback loop. Oscillations can take place only at a frequency, f_o (operating frequency), that permits the signal voltage across R_2, the input signal to Q_1, to be in phase with the output signal voltage of Q_2. At this time, the regenerative (positive) feedback voltage equals or slightly exceeds the degenerative (negative) feedback voltage. Voltages of any other frequency are attenuated by the filter circuit between the output of Q_2 and the input to Q_1, so that the feedback voltage is not adequate to maintain oscillations at any frequency other than f_o.

The degenerative feedback voltage is provided by the voltage divider, R_4 and L_1, to the emitter of Q_1. Since there is no filter circuit in this voltage divider and the resistances are constant, the amplitude of the negative feedback voltage is the same for all the frequencies that may be present in the output of Q_2.

The regenerative feedback voltage is provided by the voltage divider, consisting of a series RC filter (R_1 and C_1) and a parallel RC filter (R_2 and C_2) to the base of Q_1. If the frequency goes above f_o (increase in frequency out), the reactances of the capacitors C_1 and C_2 become very small ($X_C = \frac{1}{2\pi fC}$), making the signal voltage at the base of Q_1 very small in relationship to the negative feedback signal voltage on the emitter. On the other hand, if the frequency falls below f_o (decreased frequency out) the reactances of C_1 and C_2 become very large. In the circuit shown in figure 3, the reactance of C_1 will reduce the signal voltage "appearing" at Q_1 base to a smaller voltage in relationship to the negative feedback signal voltage on the emitter of Q_1. At f_o, the positive feedback voltage is maximum and is the same or slightly higher than the negative feedback voltage. This will cause the circuit to maintain oscillations at f_o.

Lamp L_1 in the emitter of Q_1 is an incandescent lamp. The reason for the use of this positive temperature coefficient device in the emitter of Q_1 is to stabilize the amplitude of the oscillator's output. If for some reason the amplitude of oscillations tends to increase, the current through the lamp will increase. When the current increases, the heat increases, and the lamp functions as a large resistor. A greater negative feedback voltage is developed across the increased resistance. This causes more degeneration in Q_1, which reduces the gain of Q_1 and thereby brings the output of the oscillator down. In the Wien-bridge oscillator, this provides a nearly constant amplitude out.

Twin-T oscillator

The Twin-T oscillator (sometimes called the Parallel-T or notch filter oscillator), shown in figure 4, is similar to the Wien-bridge oscillator in that the circuit would oscillate even if the Twin-T network, composed of R_5, R_6, R_8, C_1, C_2, and C_3, were eliminated. The oscillations would be over a wide range of frequencies and for all practical purposes useless.

In the Twin-T oscillator, transistor Q_1 is the oscillator and Q_2 is an emitter follower and output transistor. Transistor Q_2 also acts as a buffer amplifier to keep the oscillator from being loaded down by external circuitry.

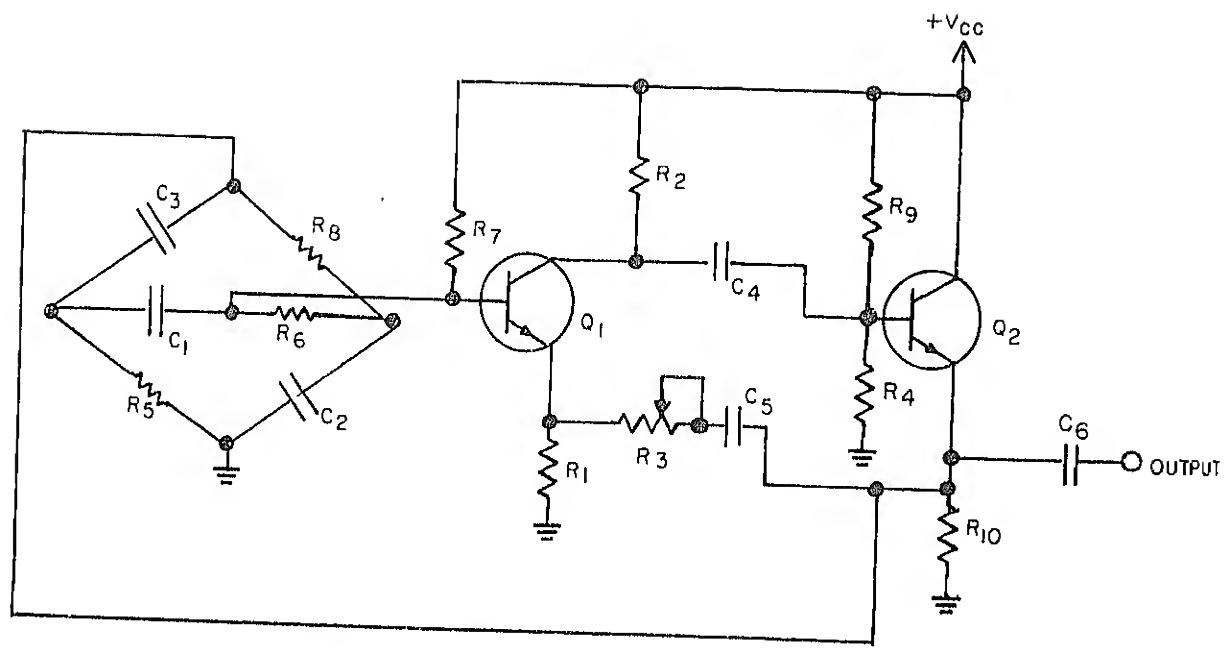


FIGURE 4 - Twin-T oscillator.

Positive feedback from the output transistor Q_2 to the oscillator transistor Q_1 is provided by capacitor C_5 and resistor R_3. Any signal felt on the base of Q_1 is amplified and inverted and applied to the base of Q_2. This provides the first 180° of phase shift. The output of Q_2 is taken off its emitter and fed back via C_5 and R_3 to the emitter of Q_1. The signal returned to the emitter of Q_1 is 180° out-of-phase with the base signal, which is the second 180° phase shift; and so oscillations are sustained. The gain of transistor Q_2 must be sufficiently high to overcome circuit losses and maintain oscillations. Resistor R_3 is normally made a variable resistor to ensure proper amplitude of positive feedback and to control the amplitude of output signal voltage. To make the Twin-T oscillator circuit selective to only one frequency, a negative feedback path including a highly selective filter network (the parallel-T filter) is provided from the emitter of Q_2 to the base of Q_1.

The Twin-T oscillator, illustrated in figure 5, is electrically the same circuit as shown in figure 4. The negative feedback path is easier to follow in figure 5.

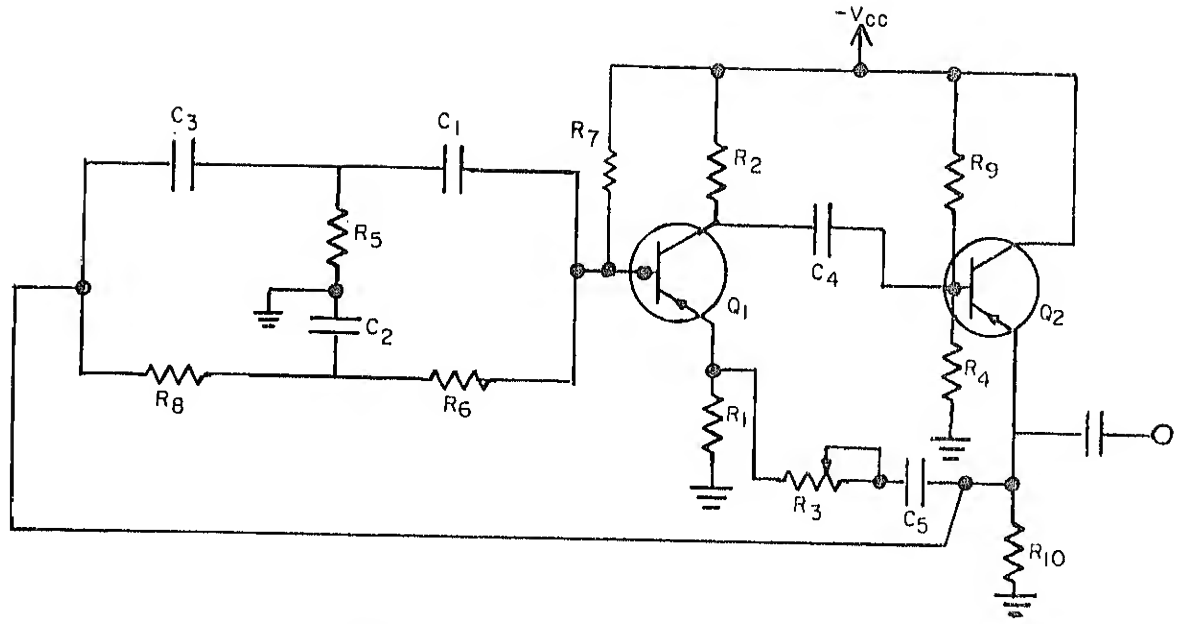
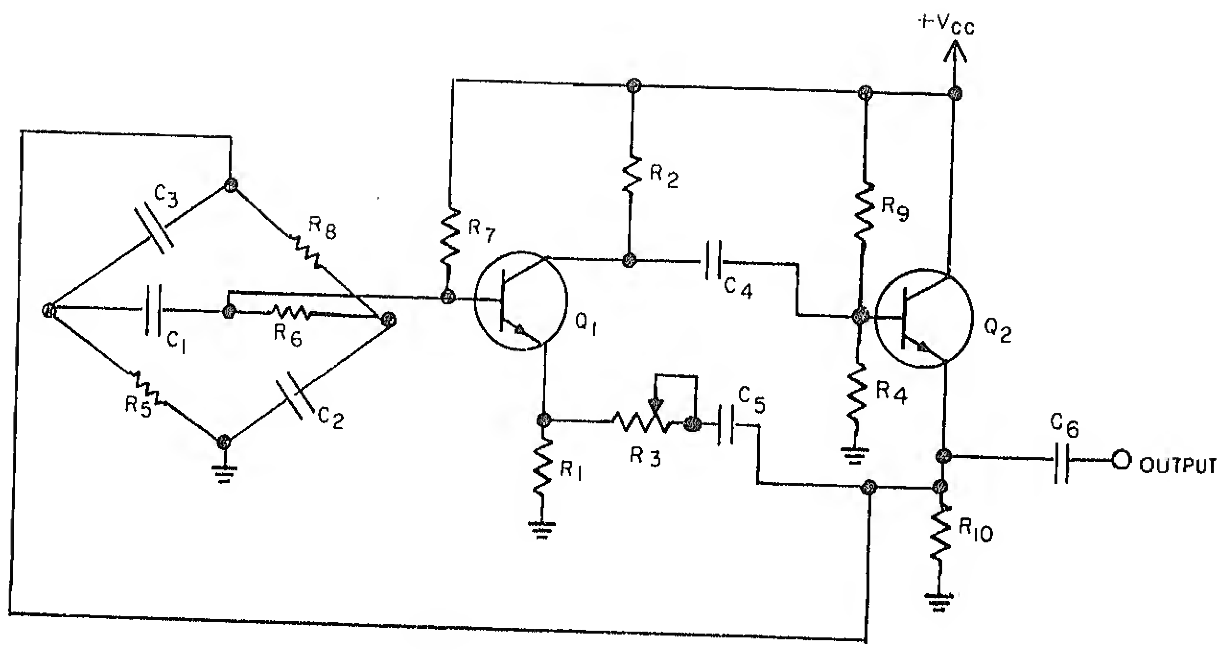


FIGURE 5 - Twin-T oscillator.

The action of the parallel-T filter circuit is such that at the desired frequency (f_o) the output of the filter network is "o", and at other than f_o, it is a higher signal voltage than the positive feedback signal voltage. At f_o, X_{C_3} is equal to R_8, X_{C_2} is equal to R_5, X_{C_1} is equal to R_6, and the values of X_{C_1} and R_6 are very large compared to all other values of reactance and resistance in the network.

The degenerative feedback has two possible paths to the base of Q_1. If the frequency tends to increase above f_o, the reactance of C_3 and C_1 decrease, decreasing the attenuation of the signal. More degenerative feedback is therefore applied to the base of Q_1. If the frequency tends to decrease below f_o, the reactance of C_2 increases and less of the degenerative signal is shunted to ground. Again more degenerative feedback is applied to the base of Q_1.

Frequencies close to f_o are highly attenuated, with less and less attenuation as the frequencies are farther and farther removed from f_o. This causes the signal voltage at the base of Q_1 to increase above f_o or below f_o, making the negative feedback signal voltage greater than the positive feedback signal voltage at the emitter. This will sharply attenuate all frequencies but f_o.



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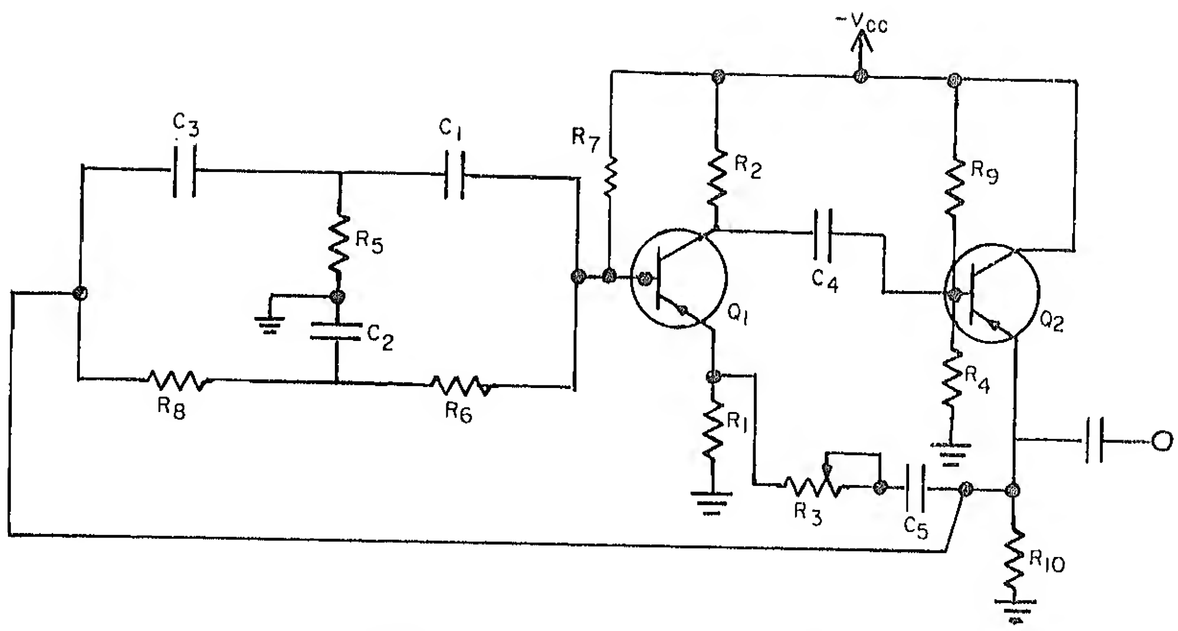

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The degenerative feedback has two possible paths to the base of Q_1. If the frequency tends to increase above f_o, the reactance of C_3 and C_1 decrease, decreasing the attenuation of the signal. More degenerative feedback is therefore applied to the base of Q_1. If the frequency tends to decrease below f_o, the reactance of C_2 increases and less of the degenerative signal is shunted to ground. Again more degenerative feedback is applied to the base of Q_1.

Frequencies close to f_o are highly attenuated, with less and less attenuation as the frequencies are farther and farther removed from f_o. This causes the signal voltage at the base of Q_1 to increase above f_o or below f_o, making the negative feedback signal voltage greater than the positive feedback signal voltage at the emitter. This will sharply attenuate all frequencies but f_o.

The Twin-T oscillator has many advantages over other types of oscillators. The output frequency is very stable, because of the sharply selective parallel-T network in the negative feedback path, which is unaffected by power supply fluctuations and circuit variations. The output amplitude can be easily varied to suit different needs. It is to be noted that in varying the resistor R_3, which controls amplitude, the frequency out will be slightly affected. The circuit will provide a constant amplitude of signal out for different load conditions.

NOTETAKING SHEET 3.5.IN

OSCILLATORS

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4. Schrader, Robert. Electronic Communication. Fourth Edition, McGraw-Hill Book Company, 1980. Chapter 13.

5. Maintenance Handbook, Device 11D13A. NAVTRADEV P-2974-I and II. Dec. 1965. Pages 3-17, 3-18, and 7-43.

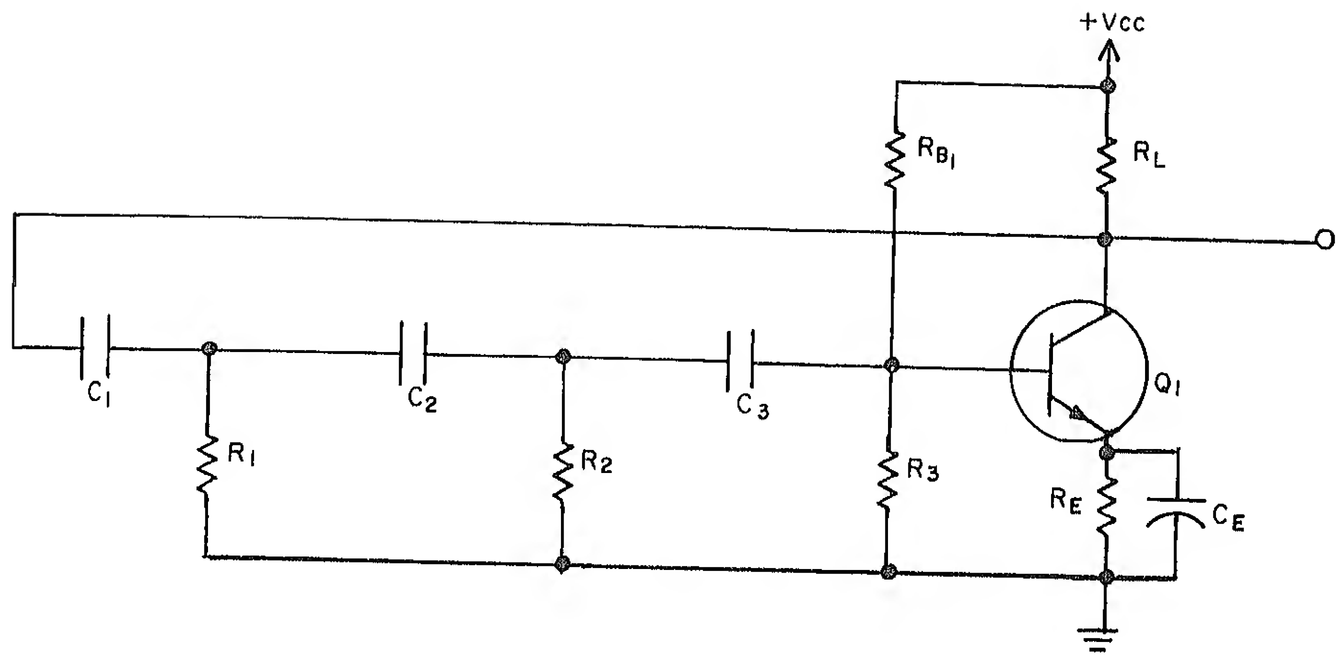
NOTETAKING OUTLINE:

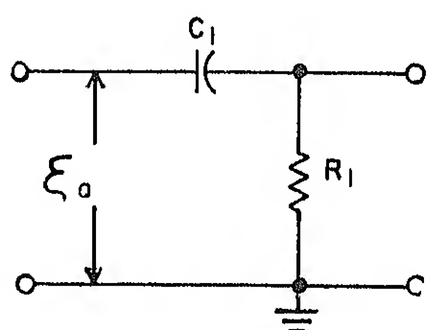
A. Purpose of an Oscillator and Principles of Operation

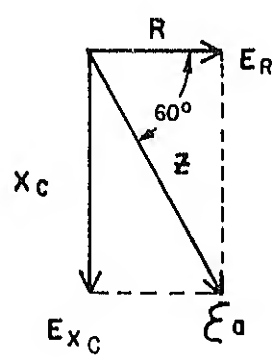
B. RC Phase-shift Oscillator

R C phase-shift oscillator

Illustrations



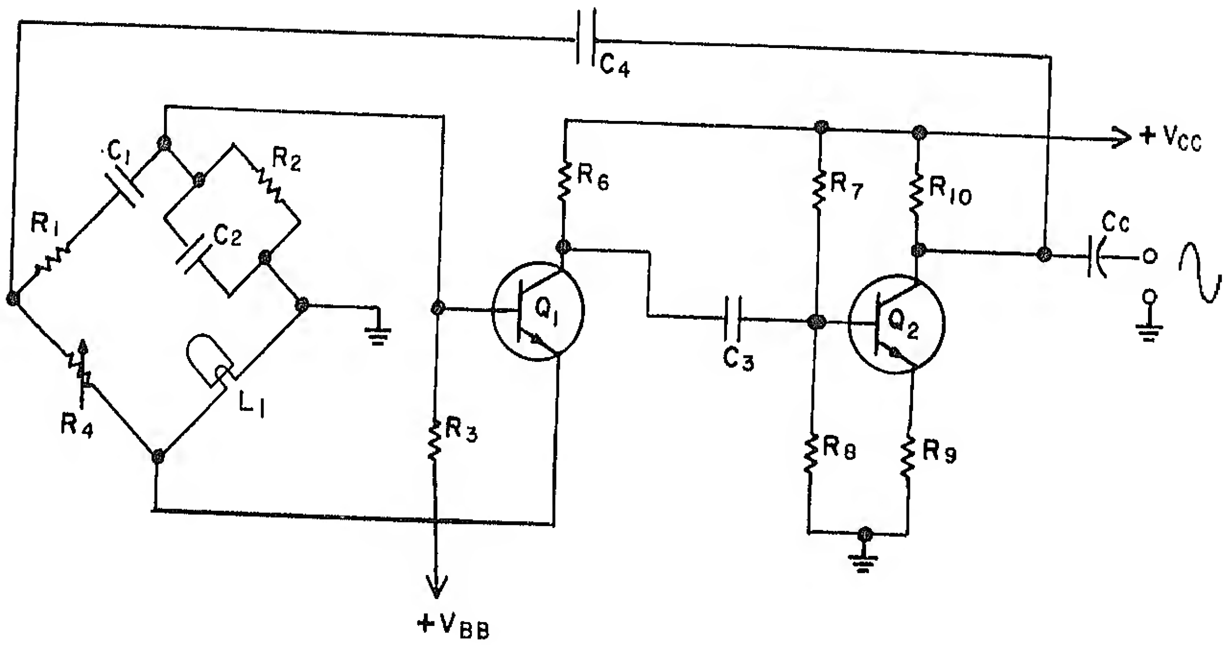


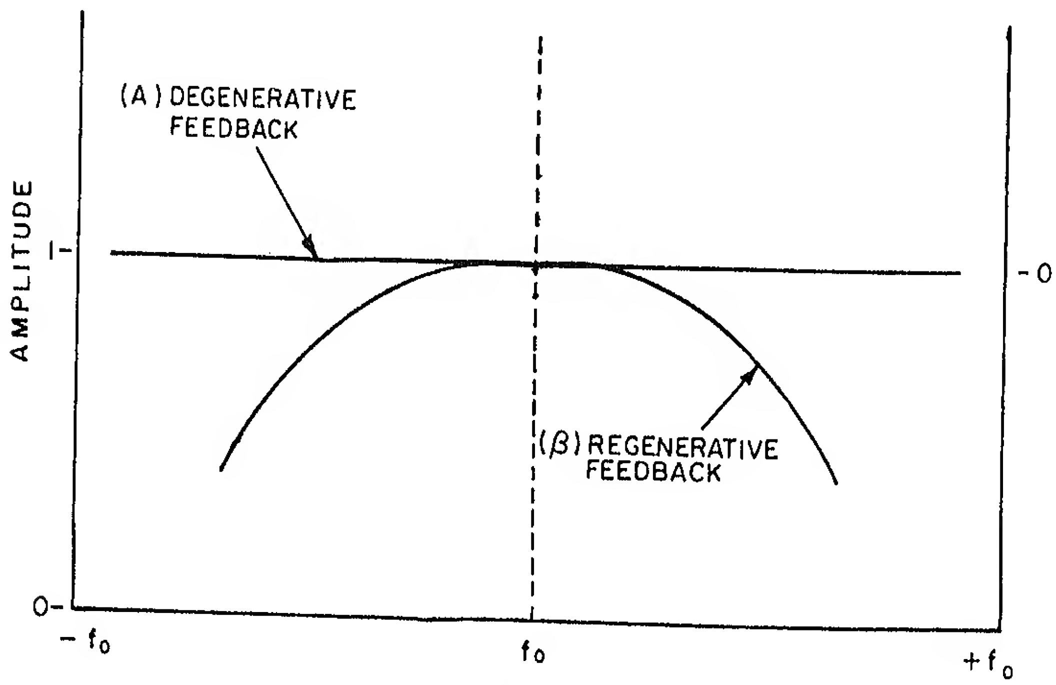


Vector analysis

C. Wien-bridge Oscillator

Wien-bridge oscillator



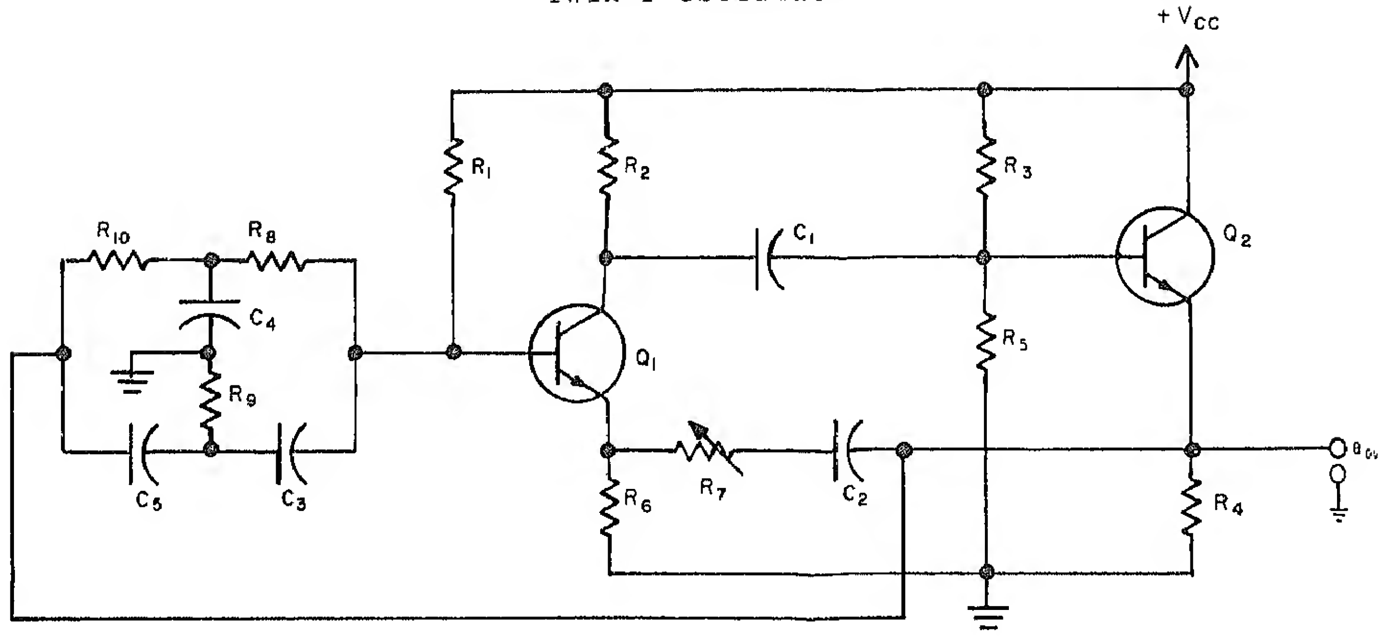


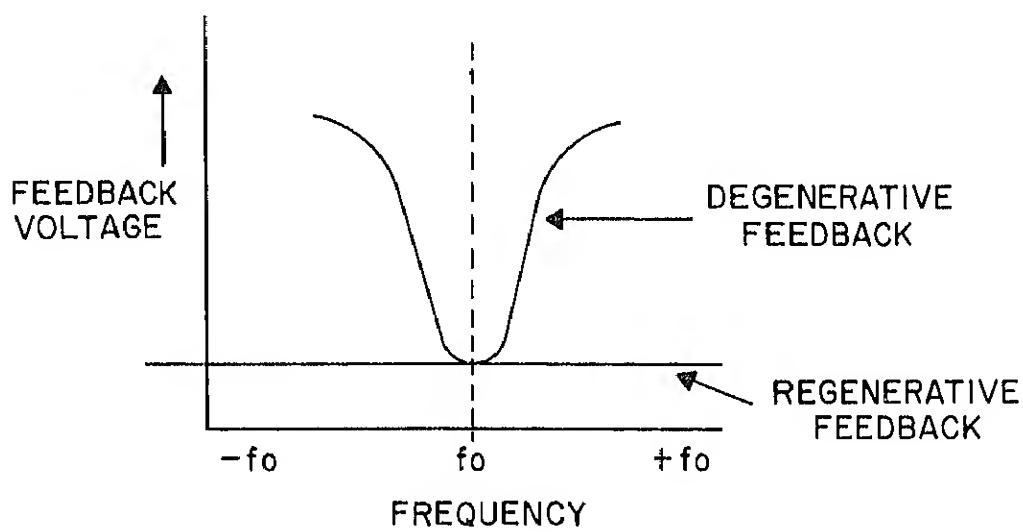
Frequency

C. Wien-bridge Oscillator

D. Twin-T Oscillator

Twin-T oscillator

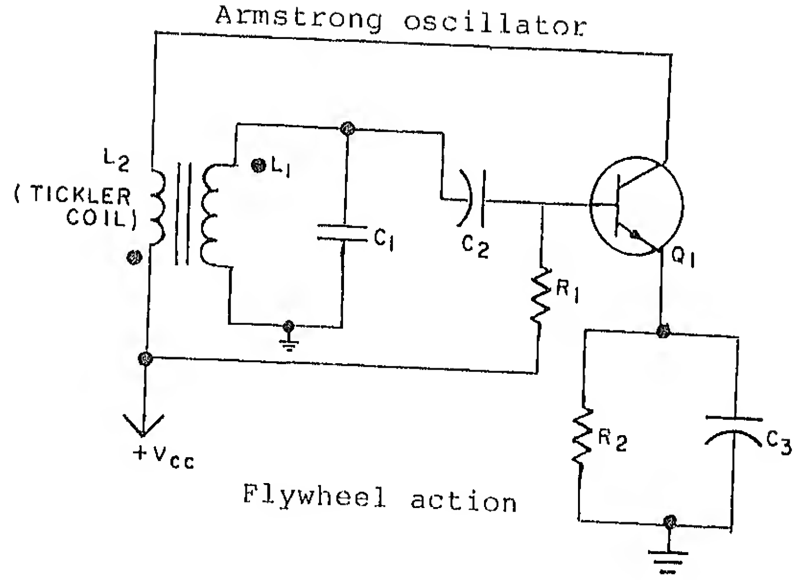




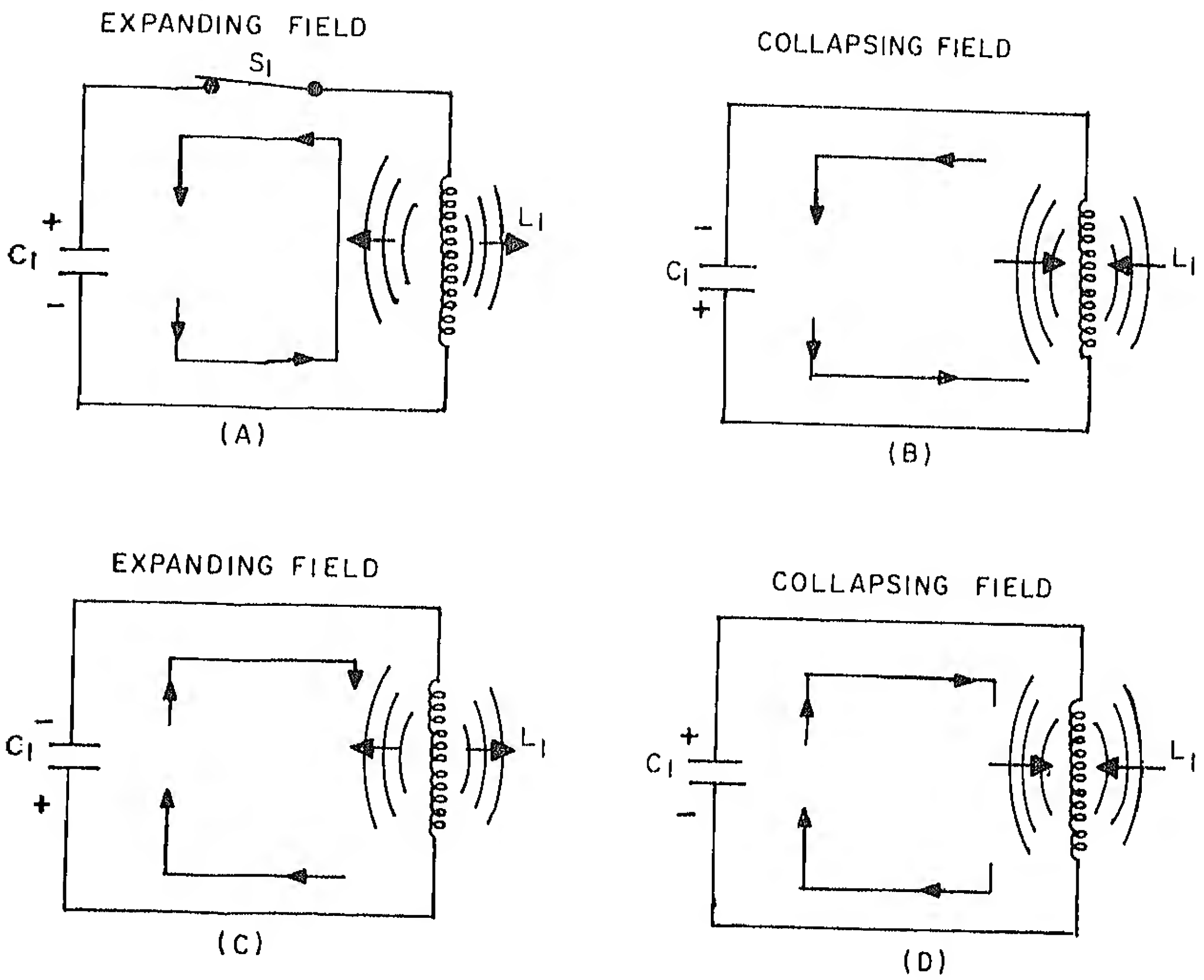
Feedback graphed

E. Armstrong Oscillator

Armstrong oscillator



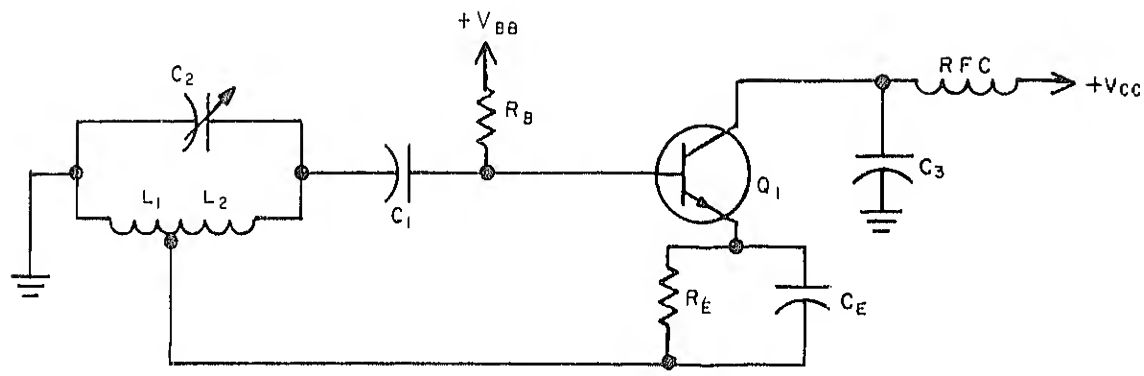
Flywheel action



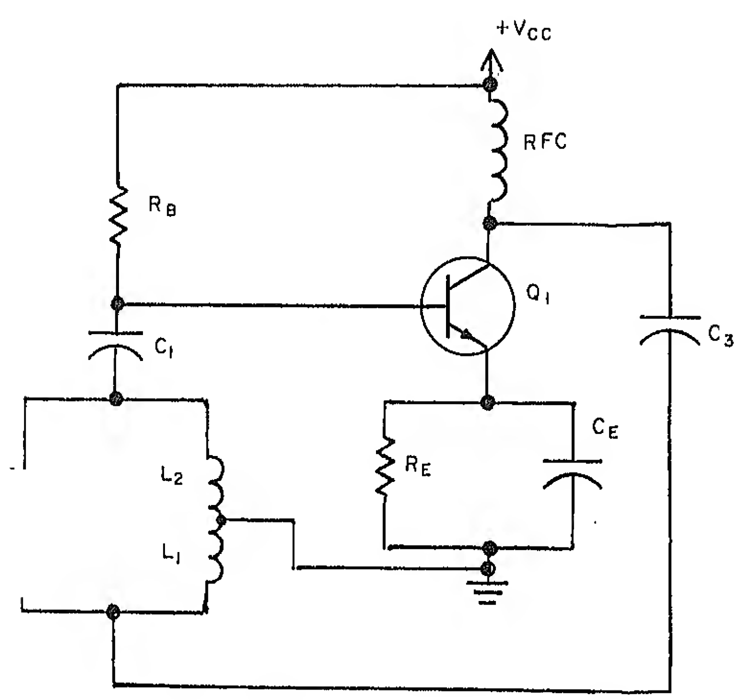
F. Hartley Oscillator

Hartley oscillator

Illustrations



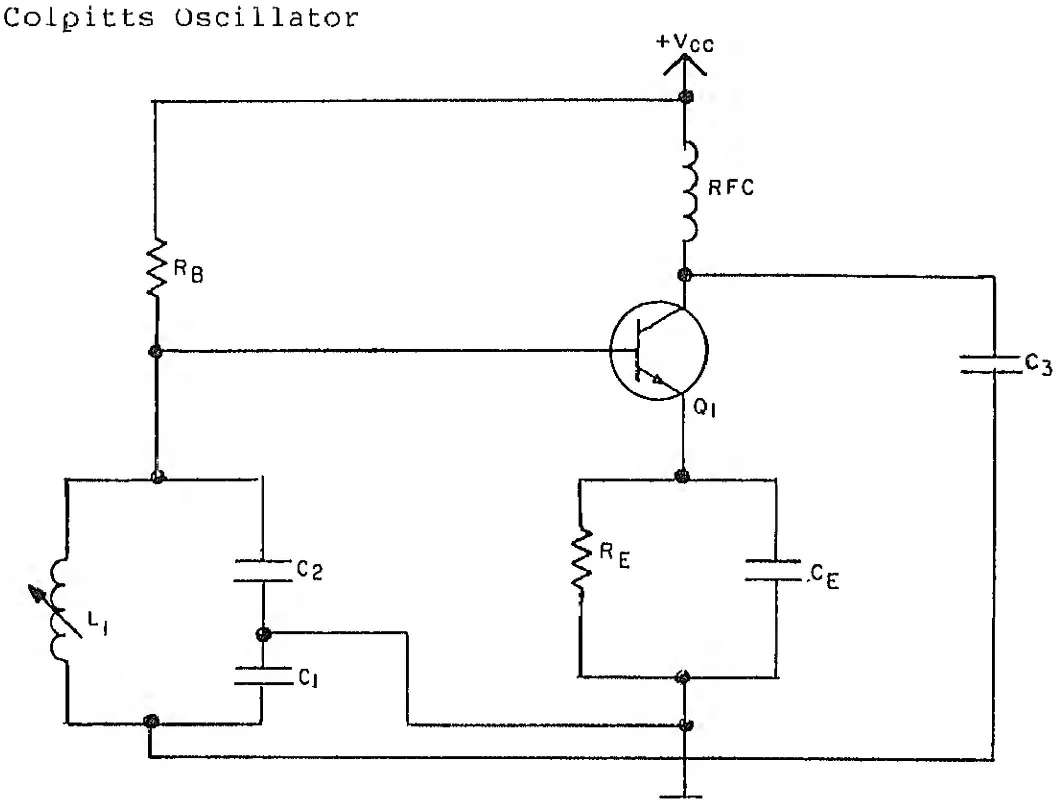
Series-fed Hartley oscillator



Shunt-fed Hartley oscillator

2. Shunt-fed Hartley oscillator

G. Colpitts Oscillator



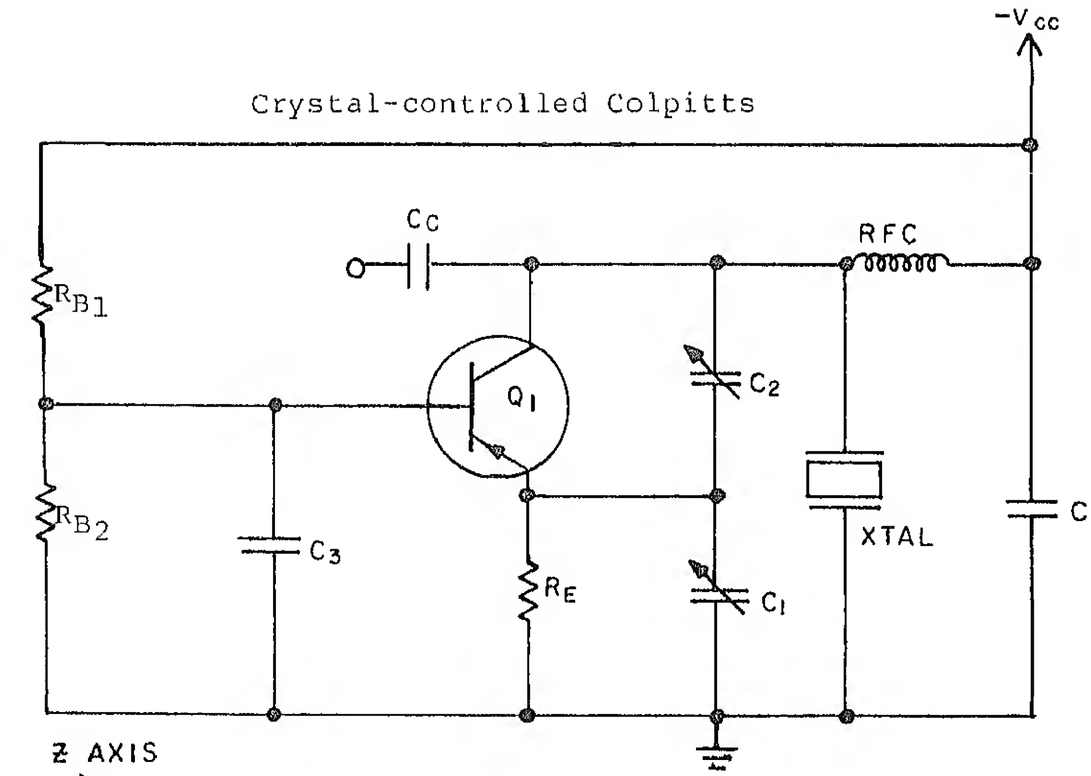
COLPITTS OSCILLATOR

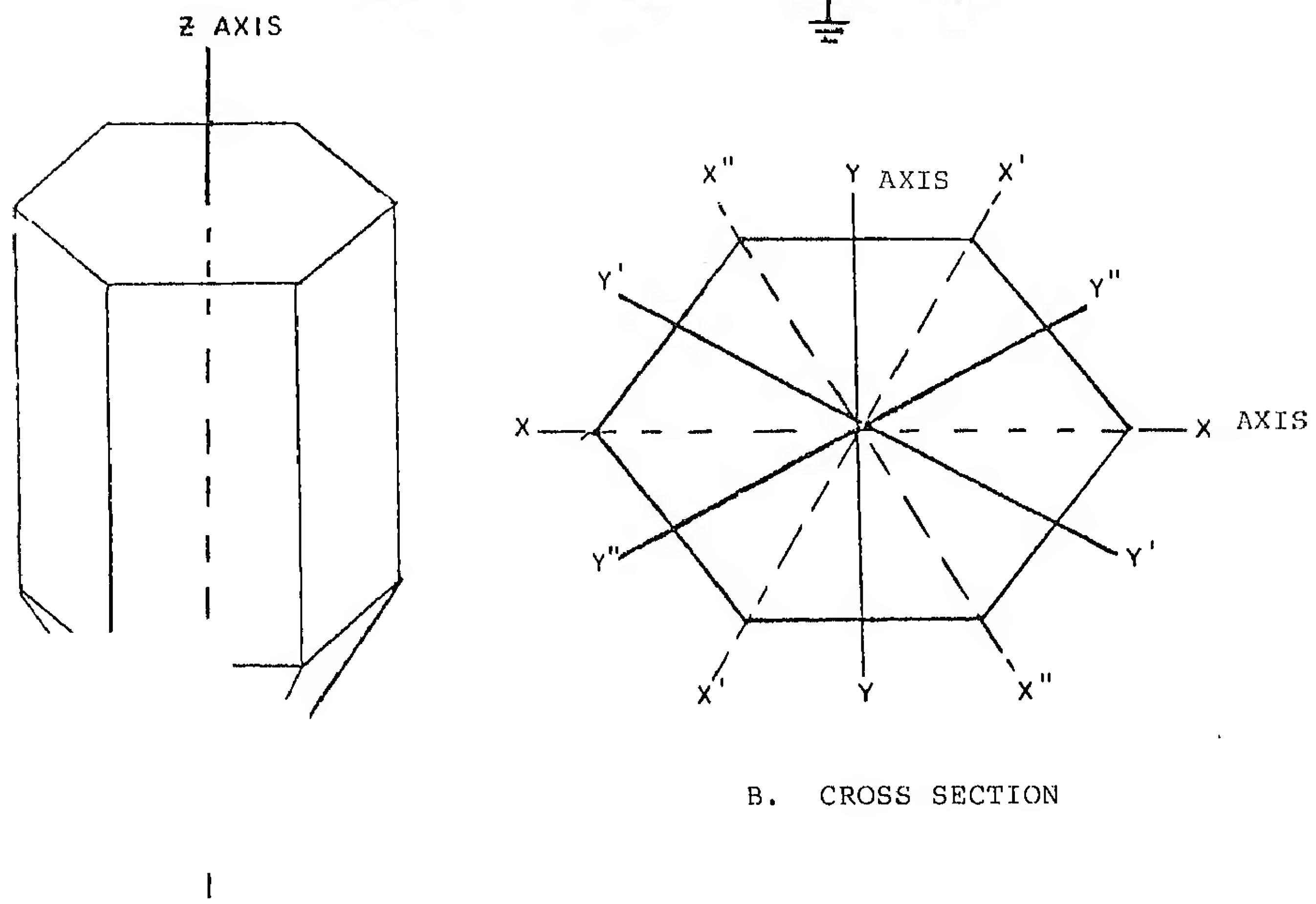
H. Crystal-controlled Oscillator

1. Definition of piezoelectric effect

2. Modes of operation

3. Colpitts crystal-controlled oscillator





B. CROSS SECTION

A. QUARTZ CRYSTAL

NOTETAKING SHEET 3.6.1N

NONSINUSOIDAL WAVEFORMS

REFERENCES:

1. Basic Electronics, Vol. II. NAVPERS 10087C. Chapter 2.

2. Electronic Circuits. NAVSHIPS 0967-000-0120. Pages 5-265 and 5-266.

3. Test Methods and Practices. NAVSHIPS 0967-000-0130. Pages 4-4 through 4-14.

NOTETAKING OUTLINE:

A. Definitions

B. Harmonic Content

1. Composition of a square wave

2. Composition of a sawtooth

3. Composition of a peaked wave

C. Bandwidth Considerations

1. Effects on a square wave

2. Effects on a sawtooth

D. Mathematical Analysis of Waveforms

1. D-c average calculations of a square wave

2. D-c average calculation of a rectangular waveform

3. D-c average calculation of a sawtooth waveform

NOTETAKING SHEET 3.7.1N

WAVE-SHAPING CIRCUITS

REFERENCES:

1. Basic Electronics, Vol.II. NAVPERS 10087C. Chapter 2, pages 13 to 23.
2. Electronic Circuit Analysis, Vol. I. NAVAIR 00-80-T-79. pages 6-1 to 6-26.
3. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 13, pages 13-67 to 13-76.
4. Test Methods and Practices. NAVSHIPS 0967-000-0130. pages 4-10 to 4-15.

NOTETAKING OUTLINE

A. RC Time Review

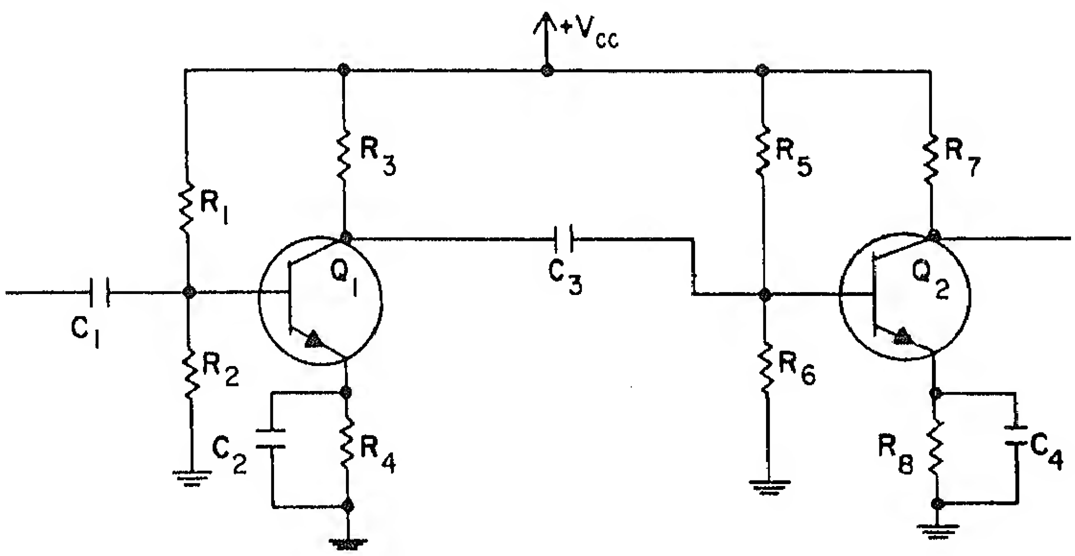
B. General Information

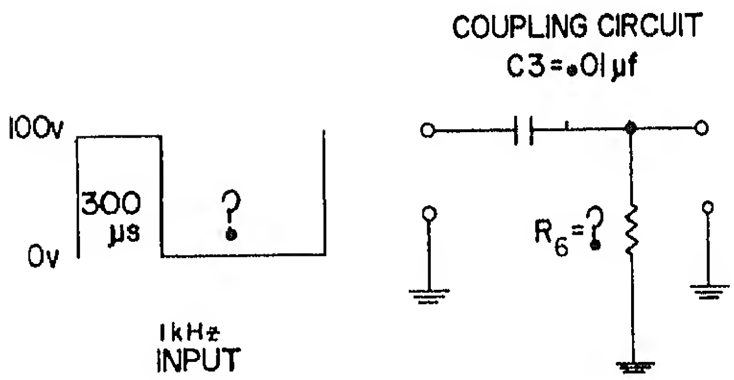
C. RC Coupling Circuits

1. A coupling circuit exhibits a --

2. The output is taken across the --

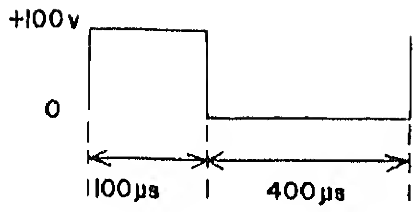
3. The desired output is a waveform that --

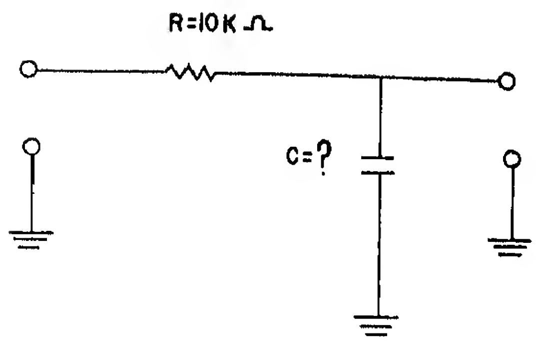


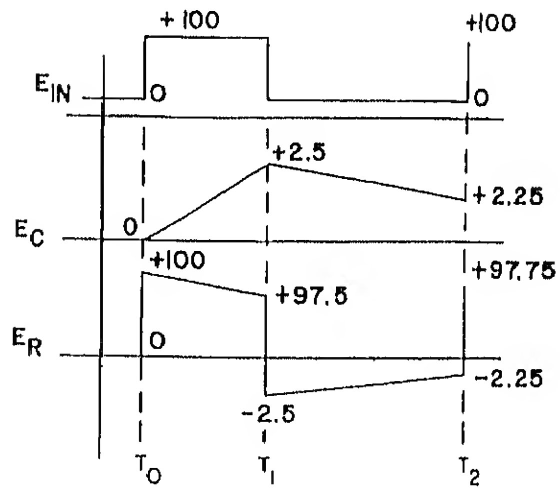


D. RC Integrator Circuits

1. An integrator is ---
2. It must exhibit a ---
3. The output is taken across the ---


+100 v
0
1100 µs
400 µs


R=10K Ω
C=?

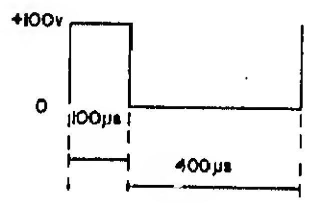

E_IN
+100
0
+100
0
E_C
0
+2.5
+2.25
+100
+97.5
+97.75
E_R
0
-2.5
-2.25
T_0
T_1
T_2

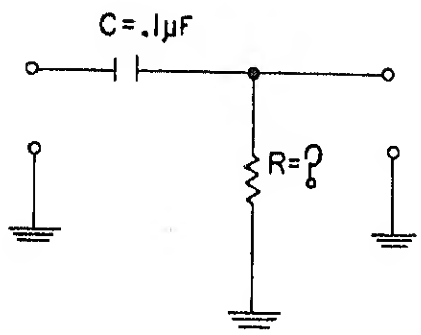
E. RC Differentiator Circuits

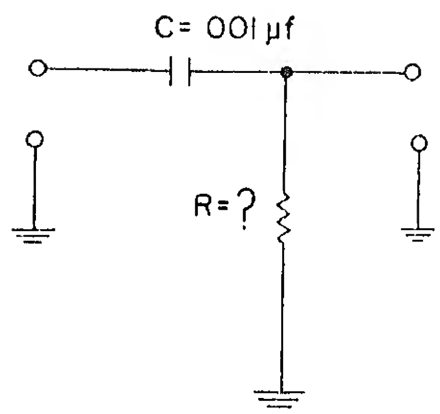
1. A differentiator is a ---

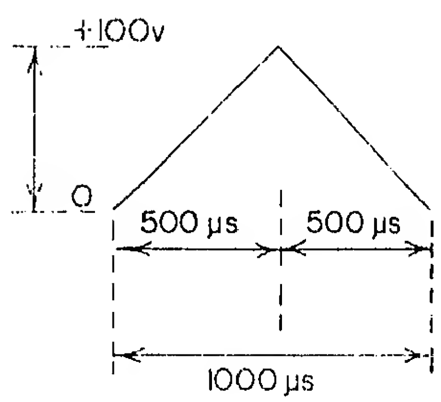
2. It must exhibit ---

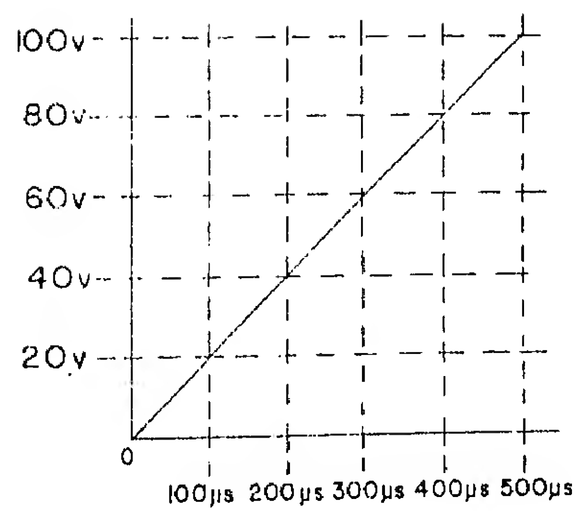
3. The output is taken across the ---

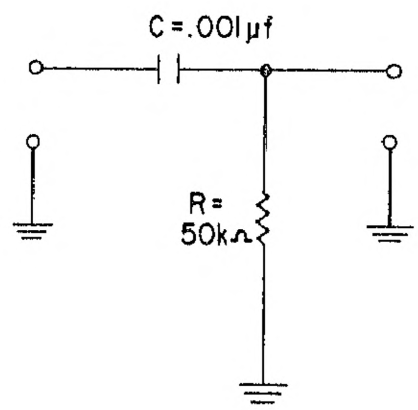




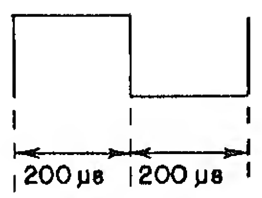

C= .001 µf
R=?

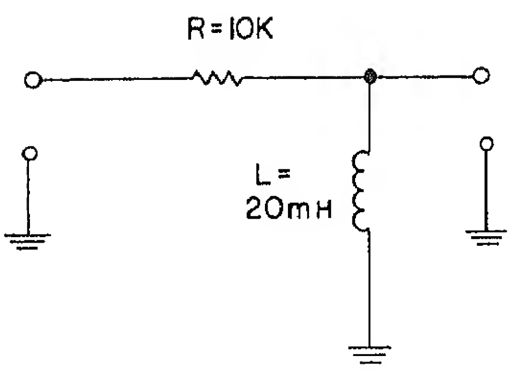

+100v
0
500 µs
500 µs
1000 µs


100v
80v
60v
40v
20v
0
100µs
200µs
300µs
400µs
500µs


C =.001µf
R =
50kΩ

F. L/R Circuits





NOTETAKING SHEET 3.8.1N

SWEEP GENERATORS

REFERENCES:

1. Basic Electronics, Vol. II. NAVPERS 10087C. Chapter 4, pages 69-74.

2. Boylestad and Nashelsky. Electronic Devices and Circuit Theory. Prentice-Hall, 1972. pages 482 to 487.

3. Electronic Circuit Analysis, Vol. I. NAVAIR 00-80T-79. pages 6-43 to 6-58.

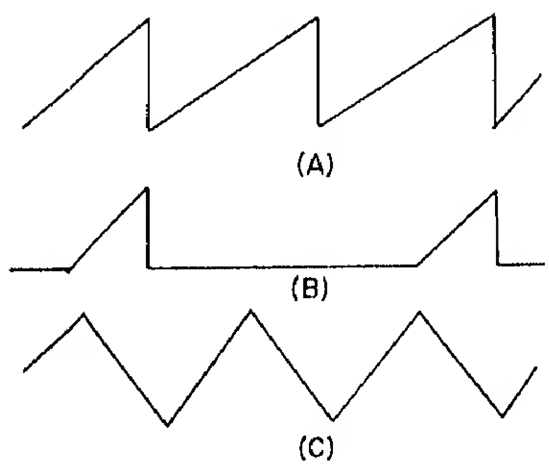
4. Electronic Circuits. NAVSHIPS 0967-000-0130. pages 8-1 to 8-22.

5. Handbook of Service Instructions. NAVWEPS 16-30 CPN4-4. Chapter 4, Section 2.

6. Maintenance Handbook, Device 11D13A, NAVTRADEV P-2974-I and II. Dec. 1965. pages 3-22 and 7-43.

NOTETAKING OUTLINE:

A. Sawtooth Waveform Nomenclature



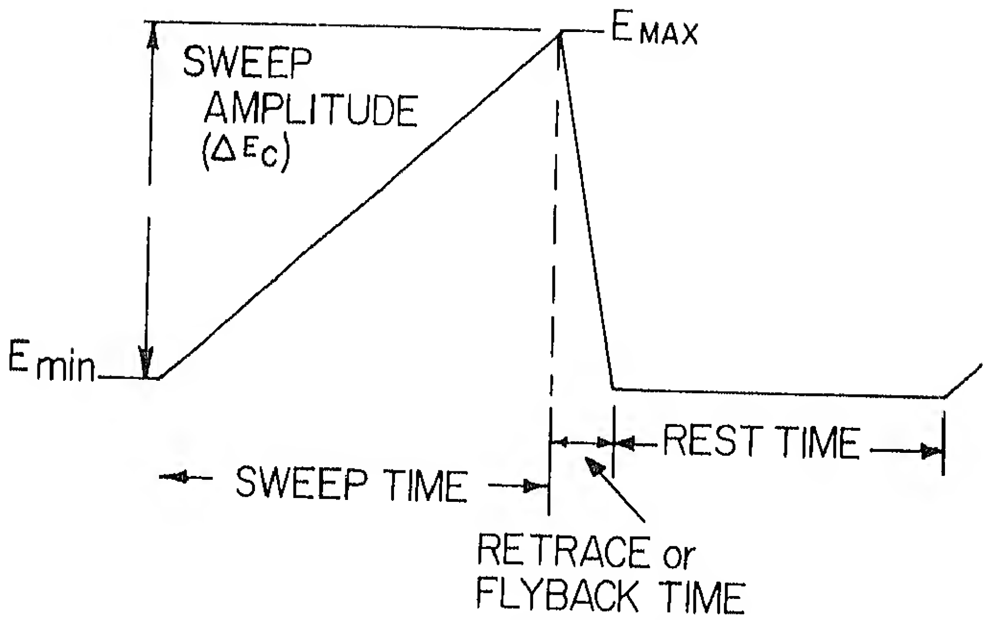


FIG.2 SAWTOOTH WITH REST TIME

B. Rate of Charge of a Capacitor

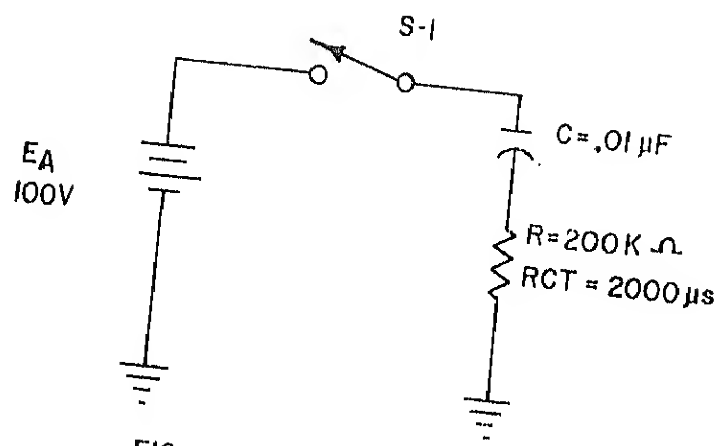
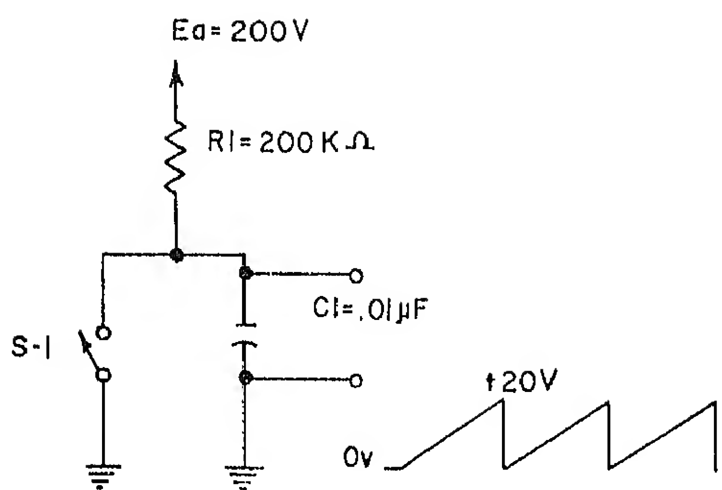
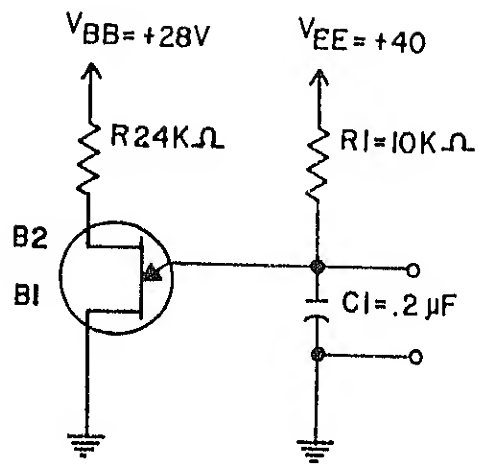


FIG. 3 SWITCHING CIRCUIT

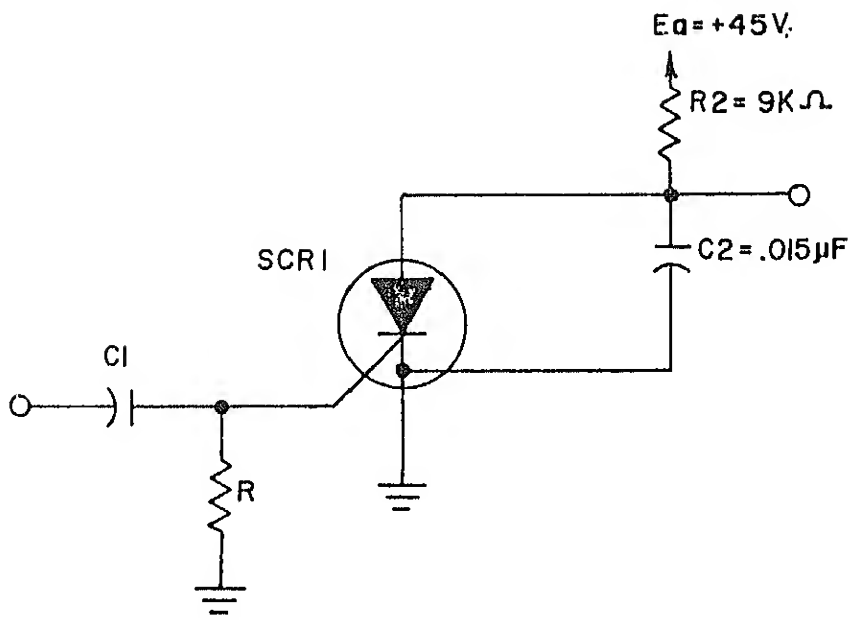
C. Basic Sawtooth Generator Operation



D. Unijunction Transistor (UJT) Sweep Generator

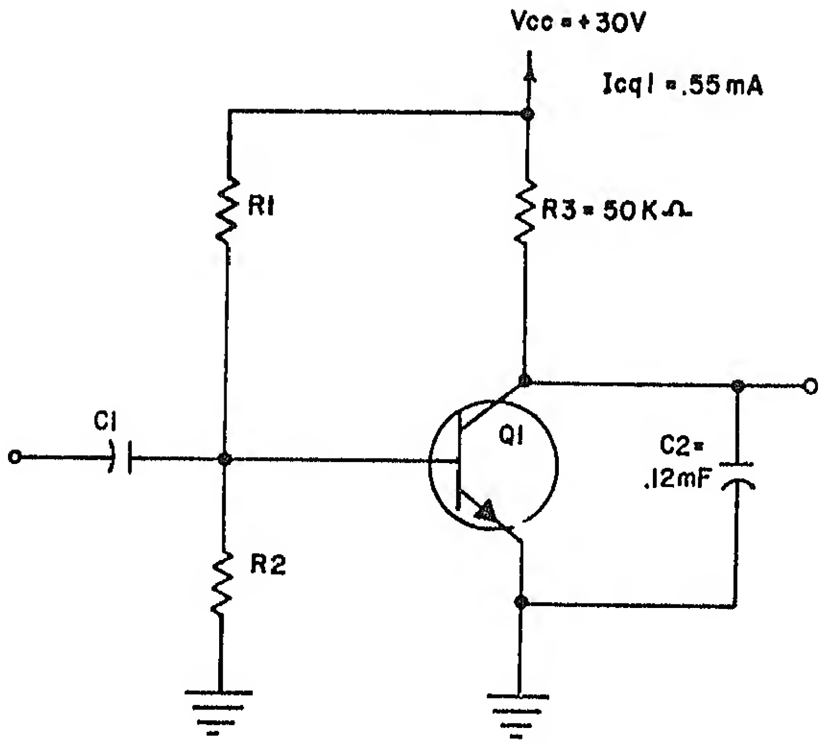


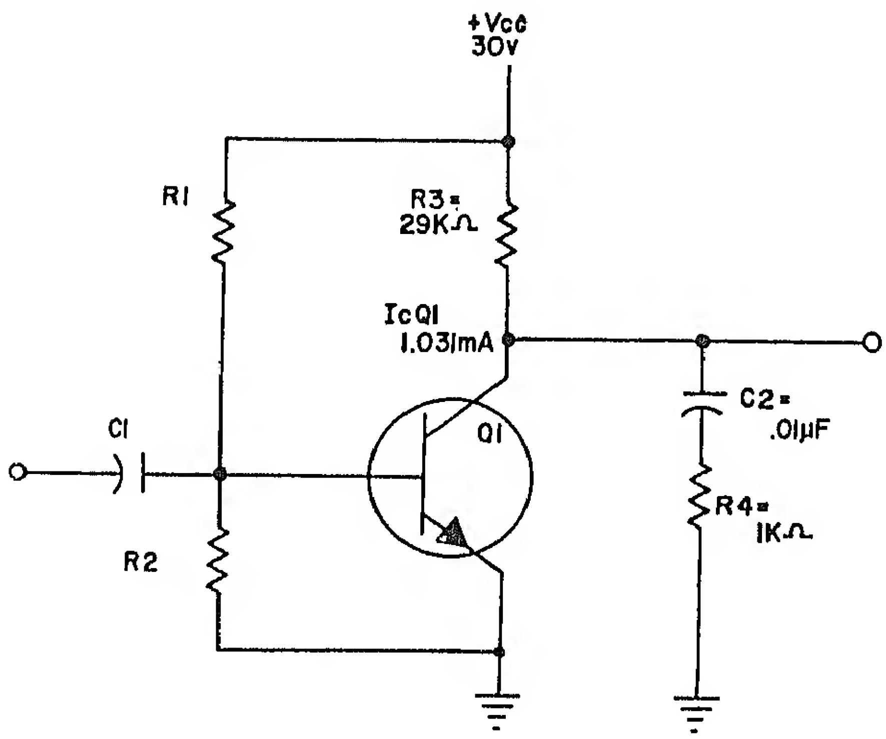
E. Silicon-controlled Rectifier (SCR) Sweep Generator



F. Gated Sweep Generators

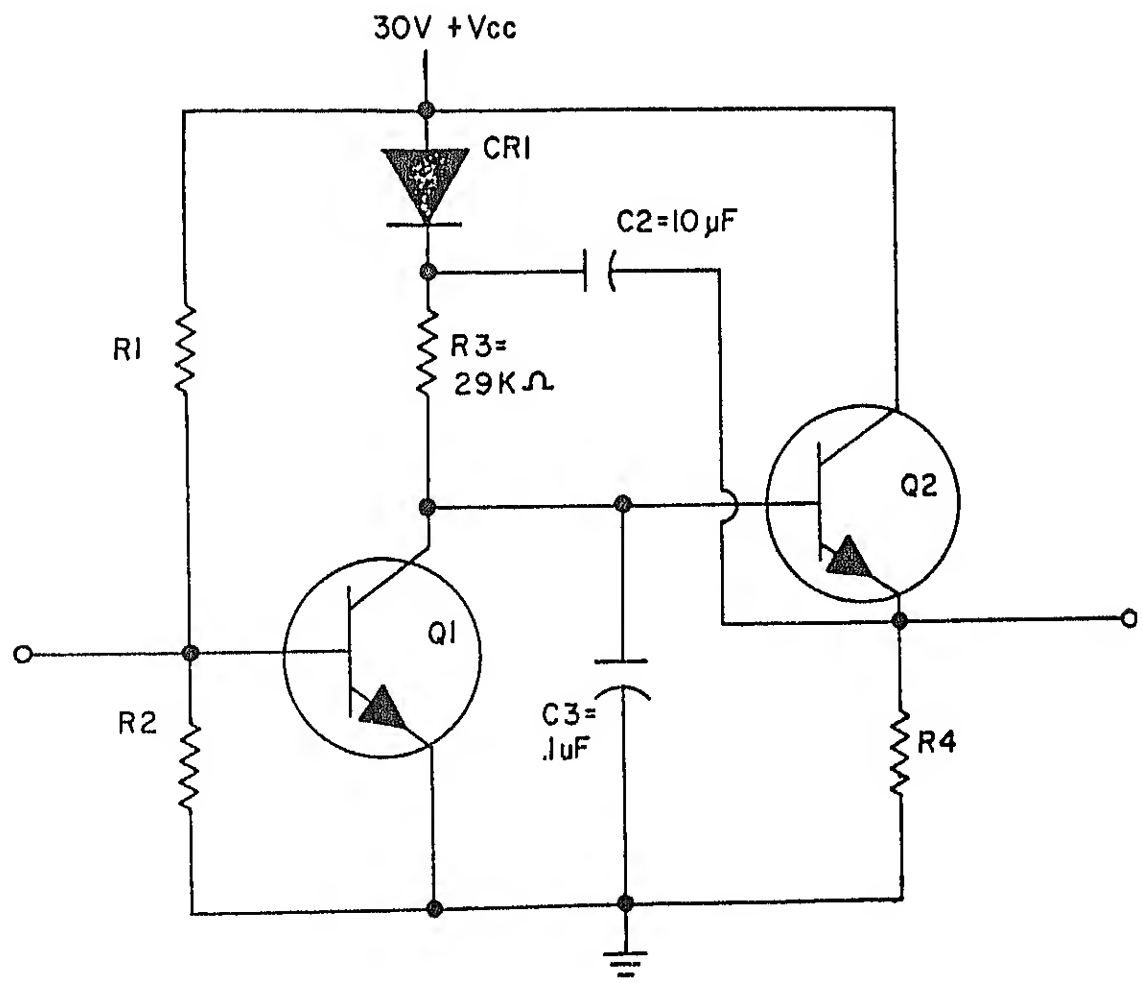
1. Transistor-gated sweep generator


Vcc = +30V
Icq1 = .55 mA
R1
R3 = 50 K Ω
C1
Q1
C2 =
.12mF
R2



2. Gated trapezoidal sweep generator

G. Gated Bootstrap Sweep Generator


30V +Vcc
CRI
C2=10 μF
R1
R3=
29K Ω
Q2
Q1
R2
C3=
.1uF
R4

NOTETAKING SHEET 3.9.IN

LIMITERS

REFERENCES:

1. Basic Electronics, Vol. II. NAVPERS 10087C. Chapter 2, pages 29 to 34.

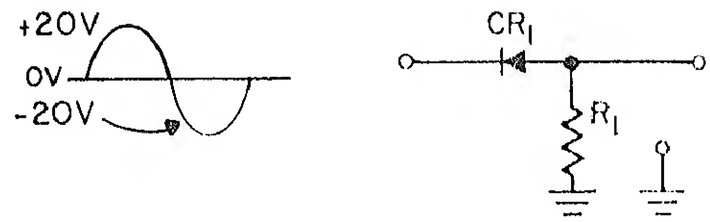
2. Electronic Circuits. NAVSHIPS 0967-000-120. Chapter 13, pages 13-13 to 13-29.

NOTETAKING OUTLINE:

A. General Information

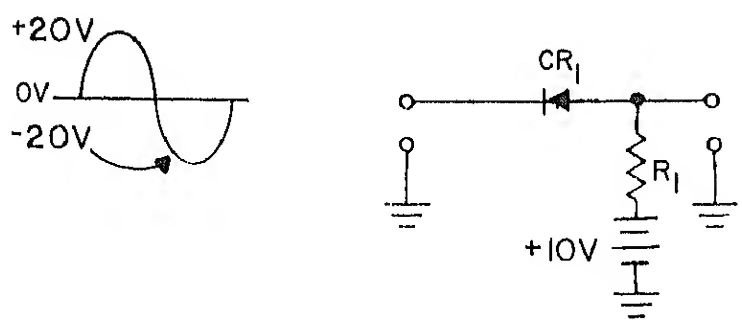
B. Series-diode Limiters

   1. Positive limiter with a zero reference



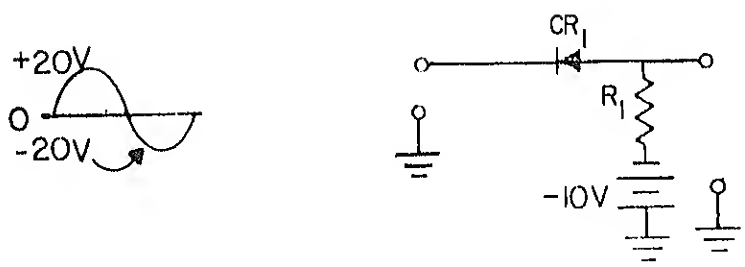
Series-diode limiter with zero reference

2. Positive limiter with a positive reference



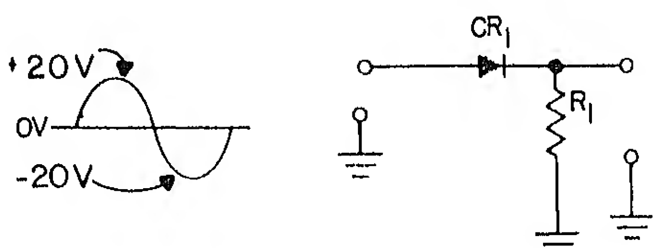
Series positive limiter with positive reference

3. Positive limiter with a negative reference



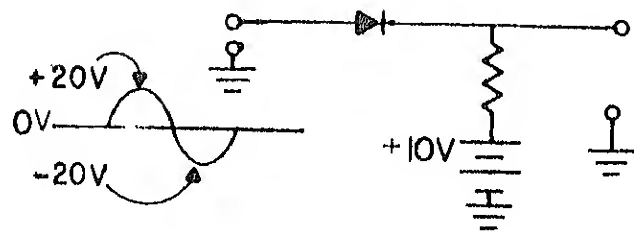
Series positive limiter with a negative reference

4. Negative limiter with a zero reference



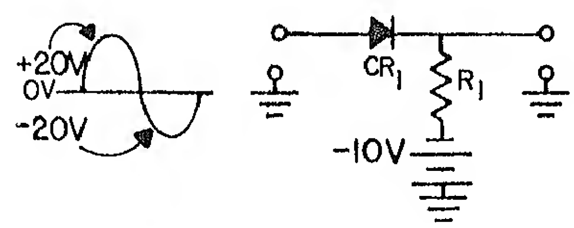
Series negative limiter with zero reference

5. Negative limiter with a positive reference



Series negative limiter with a positive reference

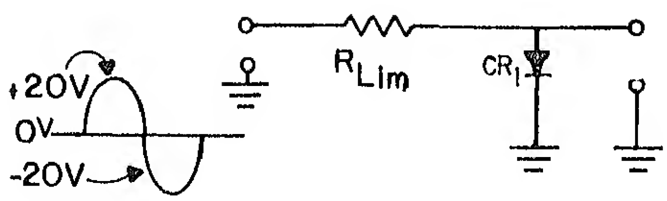
6. Negative limiter with a negative reference



Series negative limiter with a negative reference

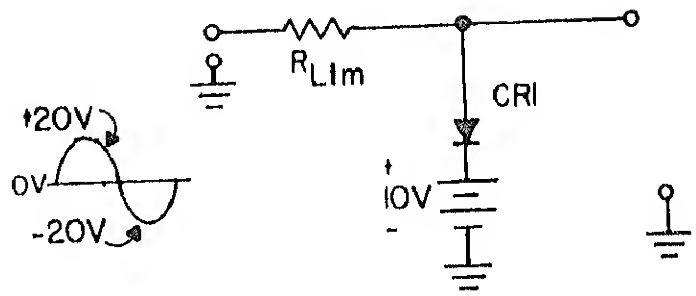
C. Shunt-diode Limiters

1. Positive limiter with a zero reference



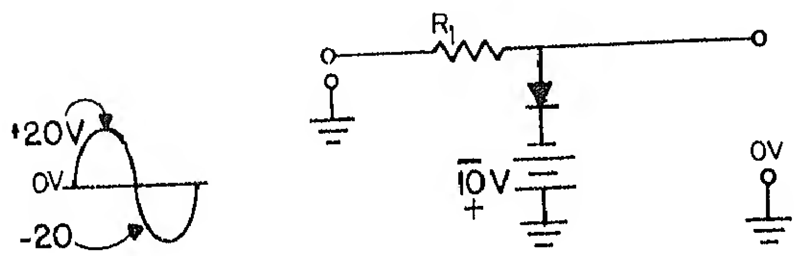
Shunt-diode positive limiter with a zero reference

2. Positive limiter with a positive reference



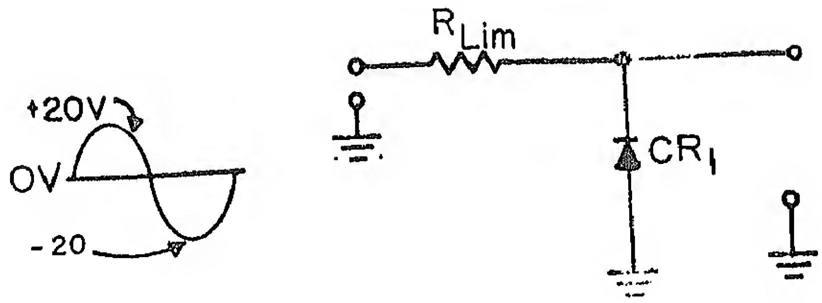
Shunt positive limiter with a positive reference

3. Positive limiter with a negative reference



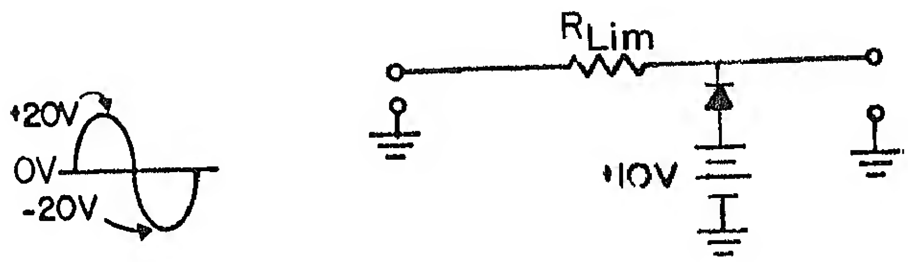
Shunt-diode positive limiter with a negative reference

4. Negative limiter with a zero reference



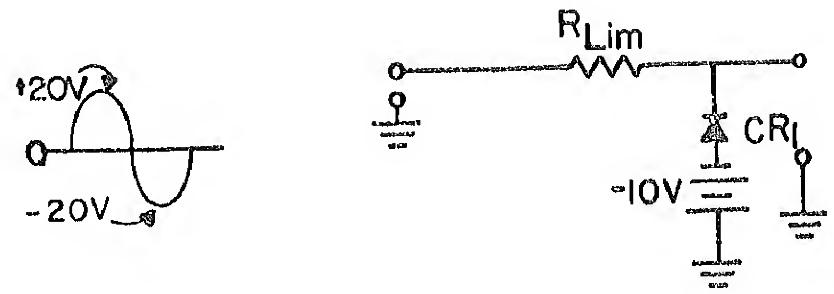
Shunt-diode negative limiter with a zero reference

5. Negative limiter with a positive reference



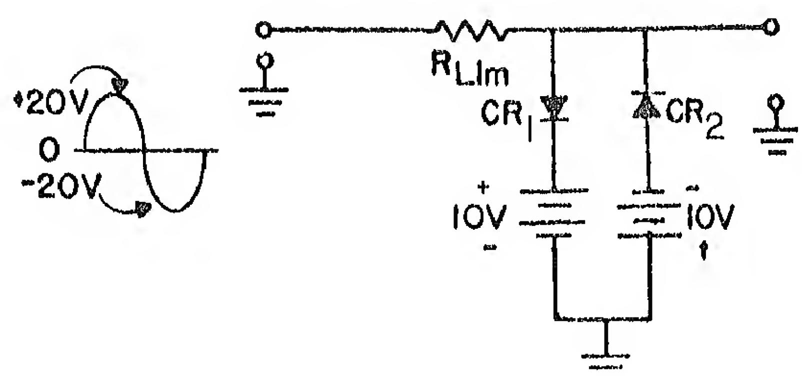
Shunt negative limiter with a positive reference

6. Negative limiter with a negative reference



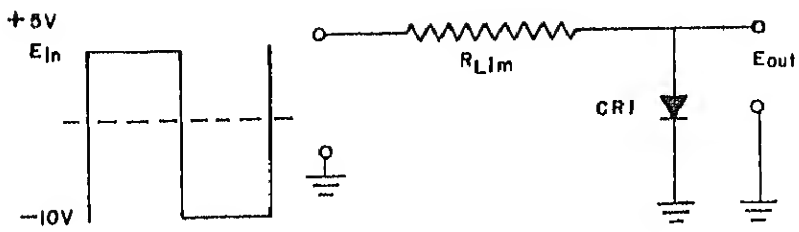
Shunt-diode negative limiter with a negative reference

D. Dual-diode Limiters

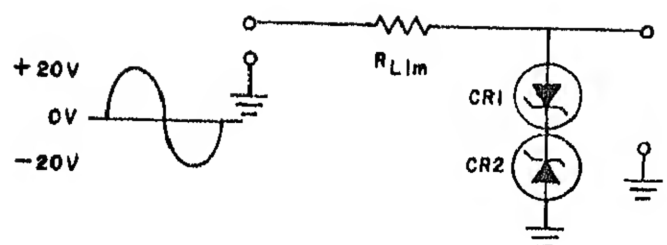


Dual-diode limiter

E. Limiting Resistor Voltage (E_R drop) Calculations



Positive shunt diode limiter



Zener diode limiting

NOTETAKING SHEET 3.10.IN

CLAMPERS

REFERENCES:

1. Basic Electronics, Vol. II. NAVPERS 10087C. Chapter 2, pages 36 to 44.

2. Electronic Circuits. NAVSHIPS 0967-000-120. Chapter 13, pages 13-50 to 13-61.

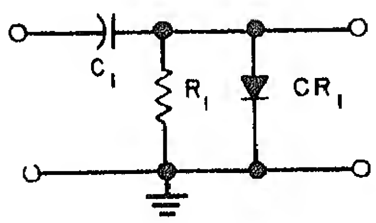
NOTETAKING OUTLINE:

A. RC Time Review

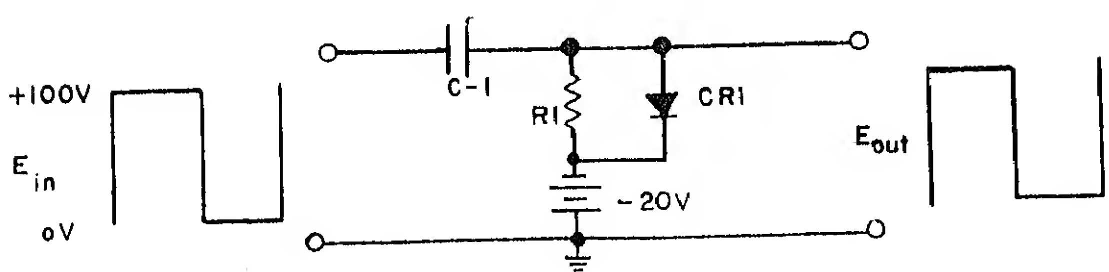
B. General Information

C. Negative Diode Clampers

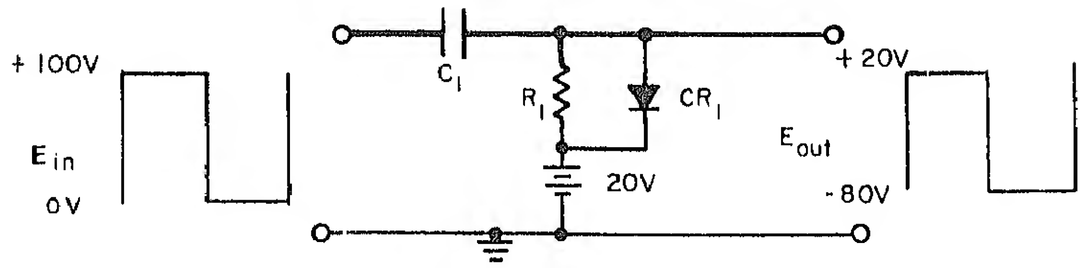
1. Negative clamper at a zero reference



2. Negative clamper with a negative reference

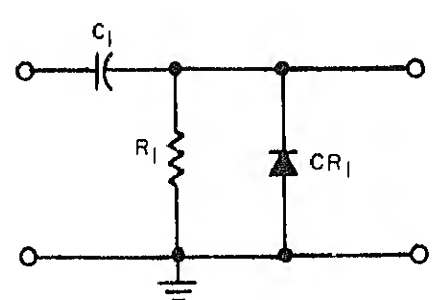


3. Negative clamper with a positive reference

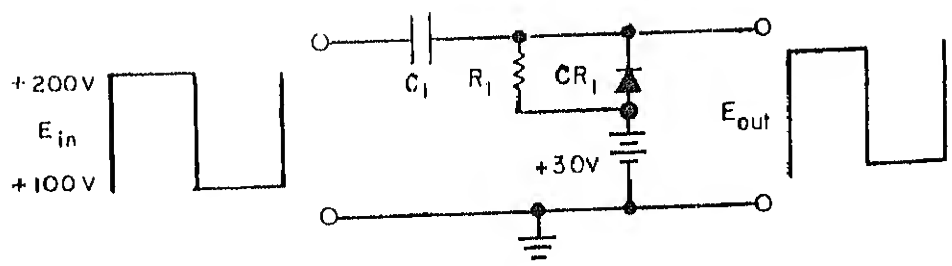


D. Positive Diode Clampers

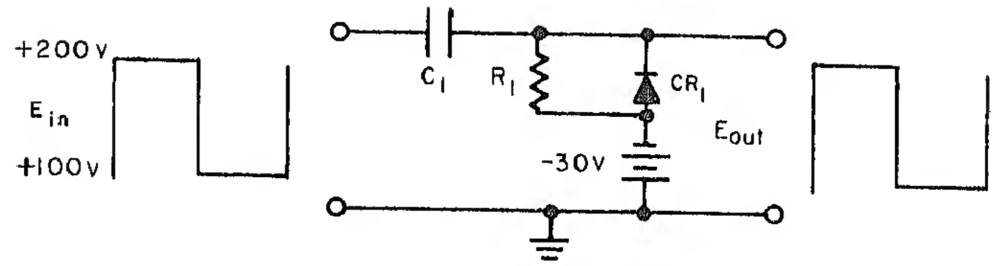
1. Positive clamper at a zero reference



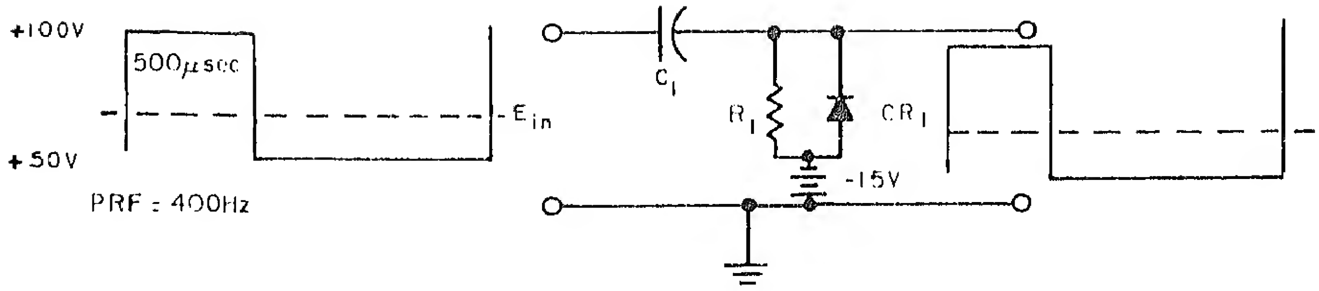
2. Positive clamper with a positive reference (bias)



3. Positive clamper with a negative reference (bias)



E. Calculating the Average Charge on the Coupling Capacitor


+100V
500μsec
+50V
PRF = 400Hz
E in
C1
R1
CR1
-15V

NOTETAKING SHEET 3.11.1N

BLOCKING OSCILLATORS

REFERENCES:

1. Basic Electronics, Vol. II. NAVEDTRA 10087-C1. Chapter 4, pages 74 to 80.

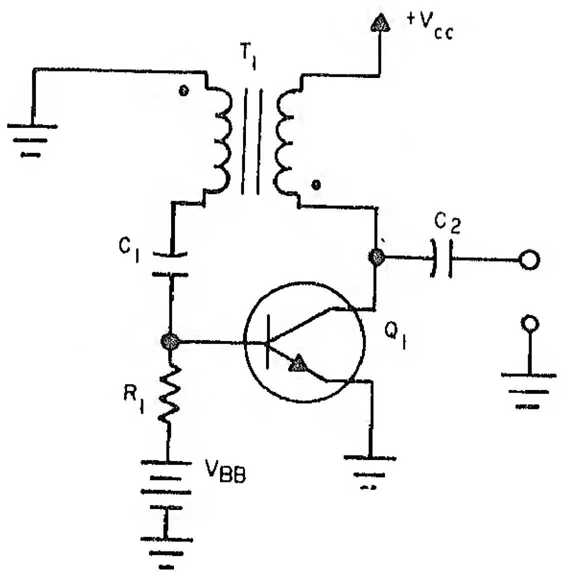
2. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 6, pages 6-134 to 6-160.

3. Electronic Circuit Analysis, Vol. I. NAVAIR 00-80-T-79. Chapter 6, pages 6-86 to 6-90.

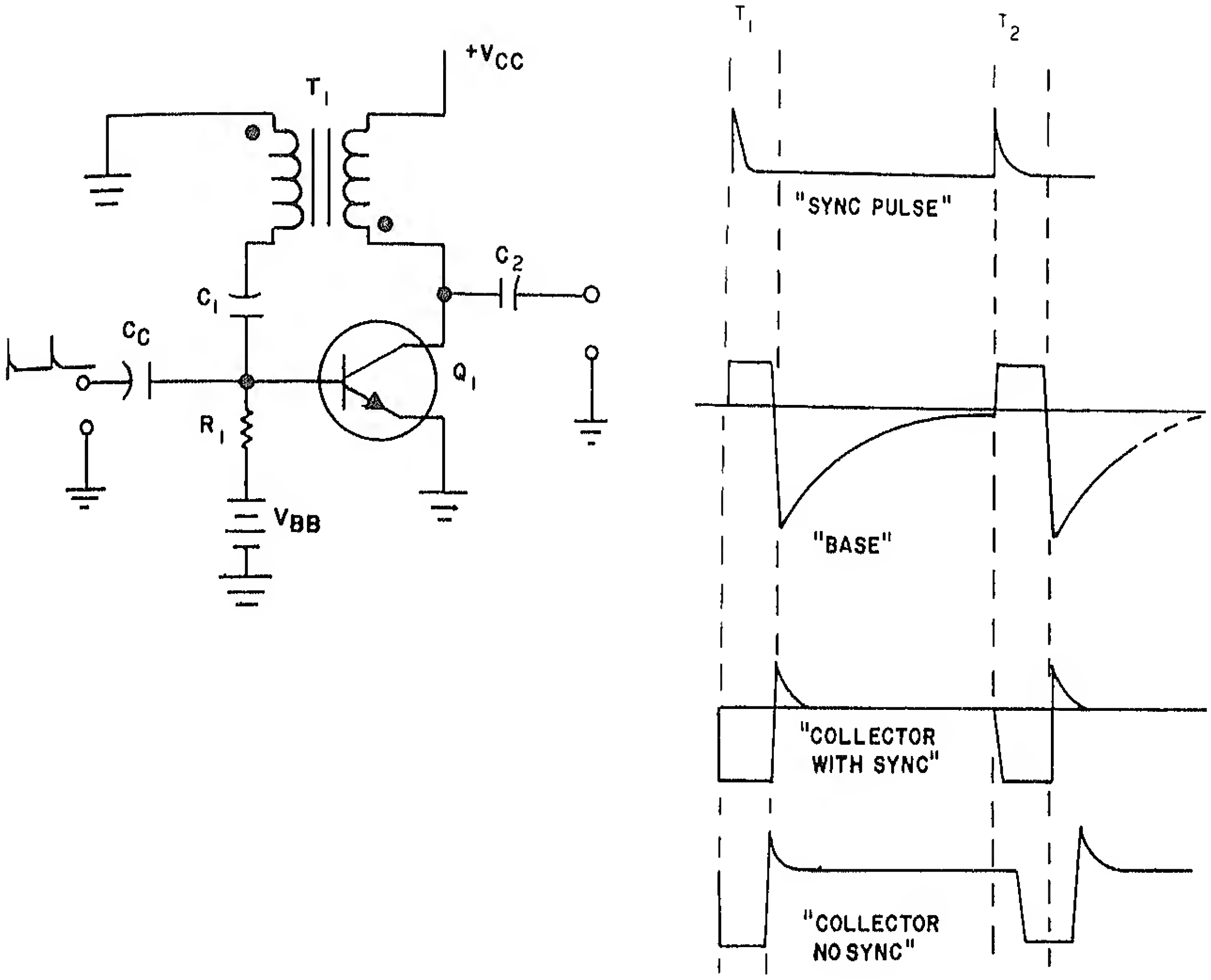
NOTETAKING OUTLINE:

A. General Information

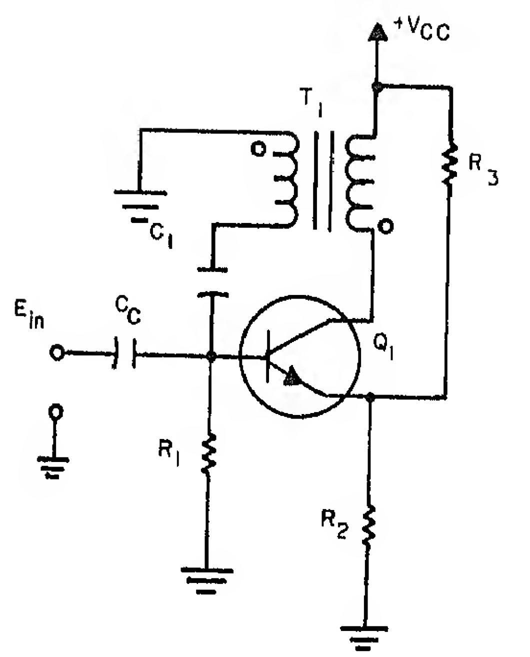
B. Free-running Blocking Oscillator

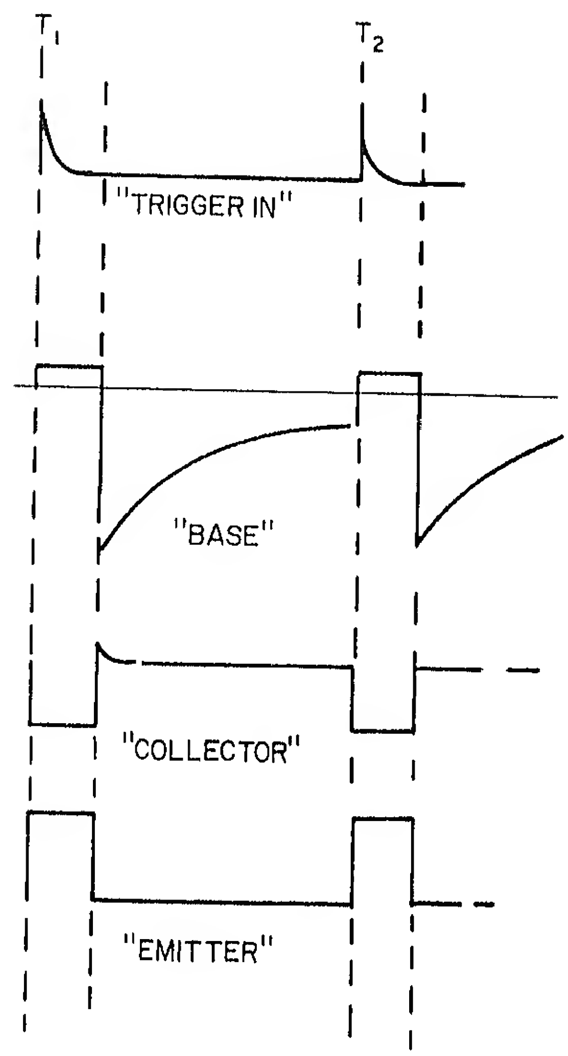


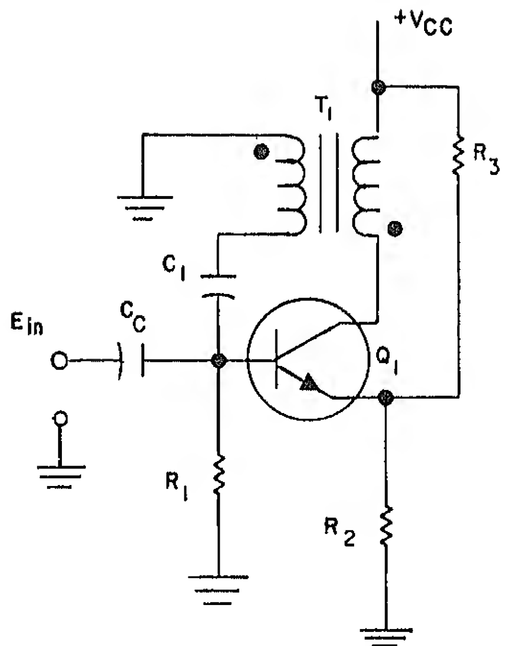
C. Synchronized Blocking Oscillator


+VCC
T1
C2
C1
CC
Q1
R1
VBB
T1
T2
"SYNC PULSE"
"BASE"
"COLLECTOR
WITH SYNC"
"COLLECTOR
NO SYNC"

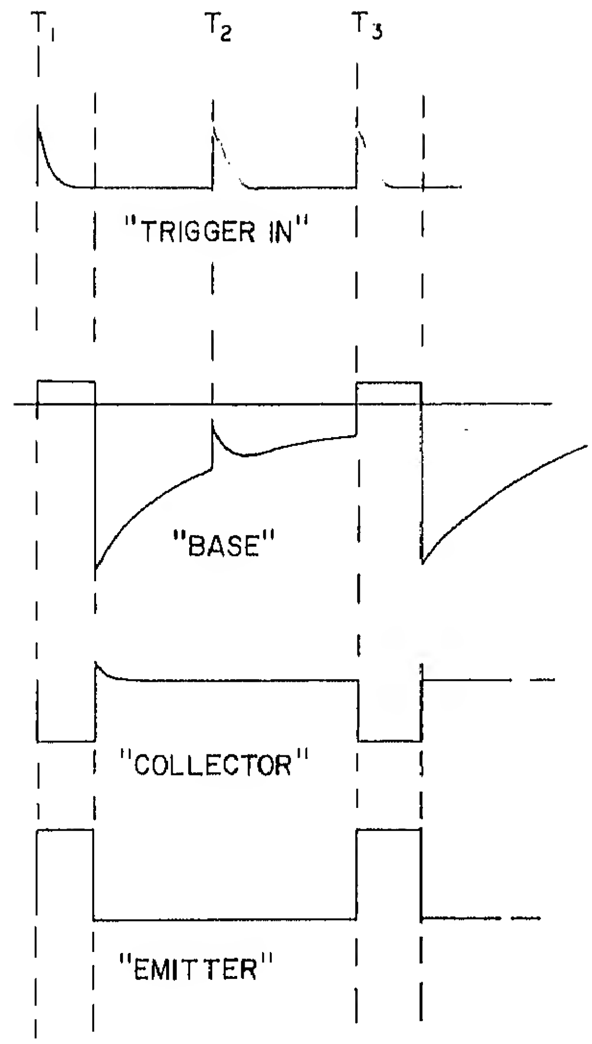
D. Triggered Blocking Oscillator, Circuit Construction and Characteristics.







+V_{CC}
T_1
R_3
C_1
E_{in}
C_C
Q_1
R_1
R_2



T_1
T_2
T_3
"TRIGGER IN"
"BASE"
"COLLECTOR"
"EMITTER"

INFORMATION SHEET 3.12.1I

MULTIVIBRATORS

INTRODUCTION

Certain areas in electronics use timing circuits to start, stop, or synchronize various circuits in a system. One method of producing these timing pulses is with multivibrators. A multivibrator is basically a two-stage RC-coupled amplifier with regenerative feed-back. A thorough understanding of the basic multivibrator circuit is a must for the RADAR technician.

REFERENCES

1. Basic Electronics, Vol. II. NAVPERS 10087-C. Chapter 3, pages 45 to 67.

2. Electronic Circuit Analysis, Vol. I. NAVAIR 00-80-T-79. Chapter 6, pages 6-56 to 6-79.

3. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 7, pages 7-1 to 7-64.

General

A multivibrator is a form of relaxation oscillator. A relaxation oscillator is one that makes use of the transient represented by the charge and discharge of a capacitance or inductance through a resistance.

Free-running collector-coupled multivibrator

Looking at the action from the point of view of transients, there are four different conditions that exist during one cycle of operation. (See figure 1.)

They are:

1. An extremely rapid change from Q_1 conducting to Q_2 conducting.

2. A long period during which Q_1 is cut off and the circuit is relaxed.

3. A second rapid change as Q_1 conducts, driving Q_2 beyond cutoff.

4. A long period during which Q_2 is cut off and the circuit is relaxed.

The cycle repeats as condition "1" follows condition "4".

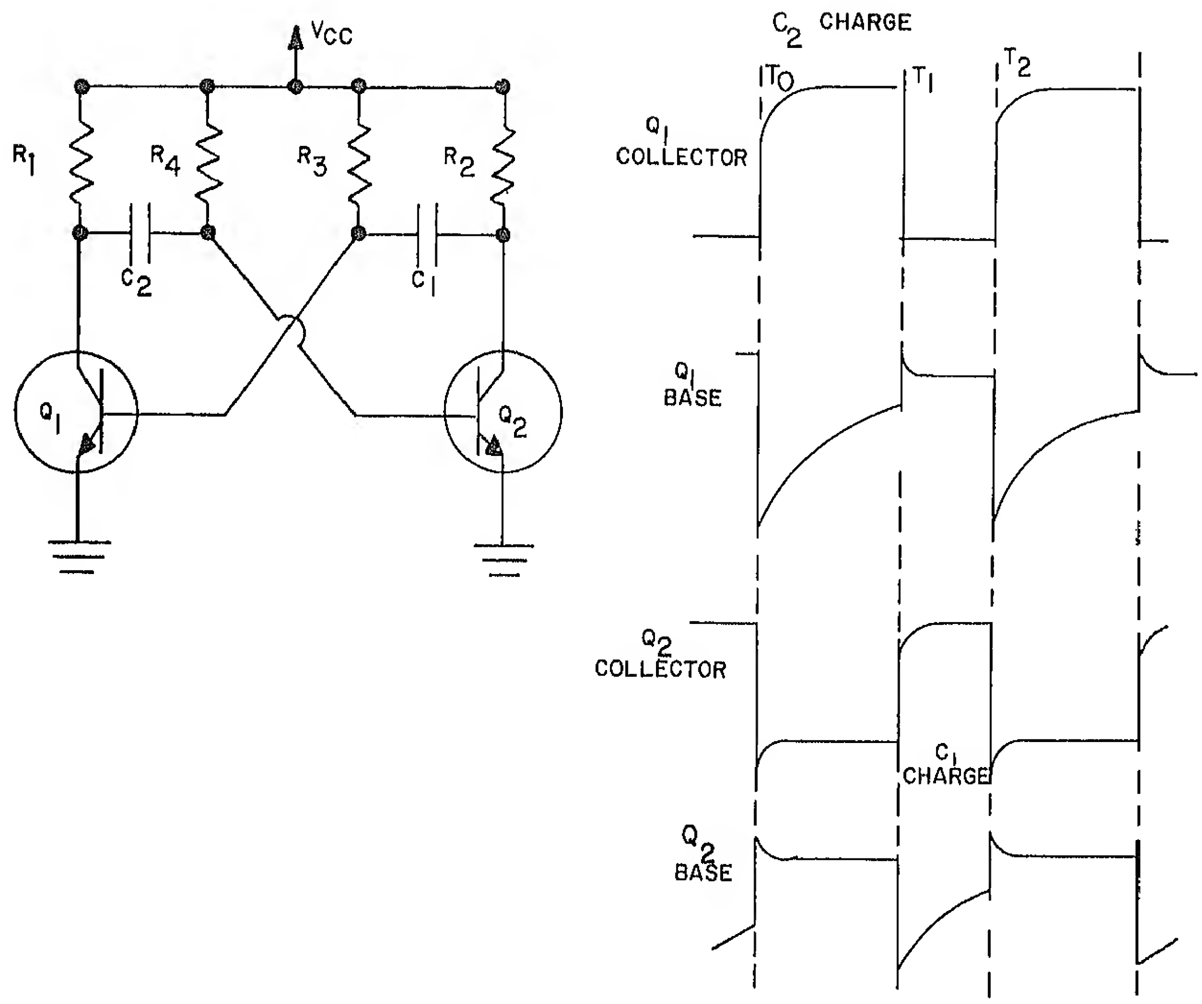


FIGURE 1 - Four conditions existing in free-running collector-coupled multivibrator.

Circuit operation (figure 2)

Assume Q_1 conducts first. The voltage on the collector becomes negative. This is felt on the base of Q_2 and drives it beyond cutoff. The collector of Q_2 becomes positive in regard V_{CC} and is felt on the base of Q_2, which causes Q_1 to go to saturation. As Q_2's collector becomes positive, C_1 charges through the emitter to the base resistance of Q_1 and R_2.

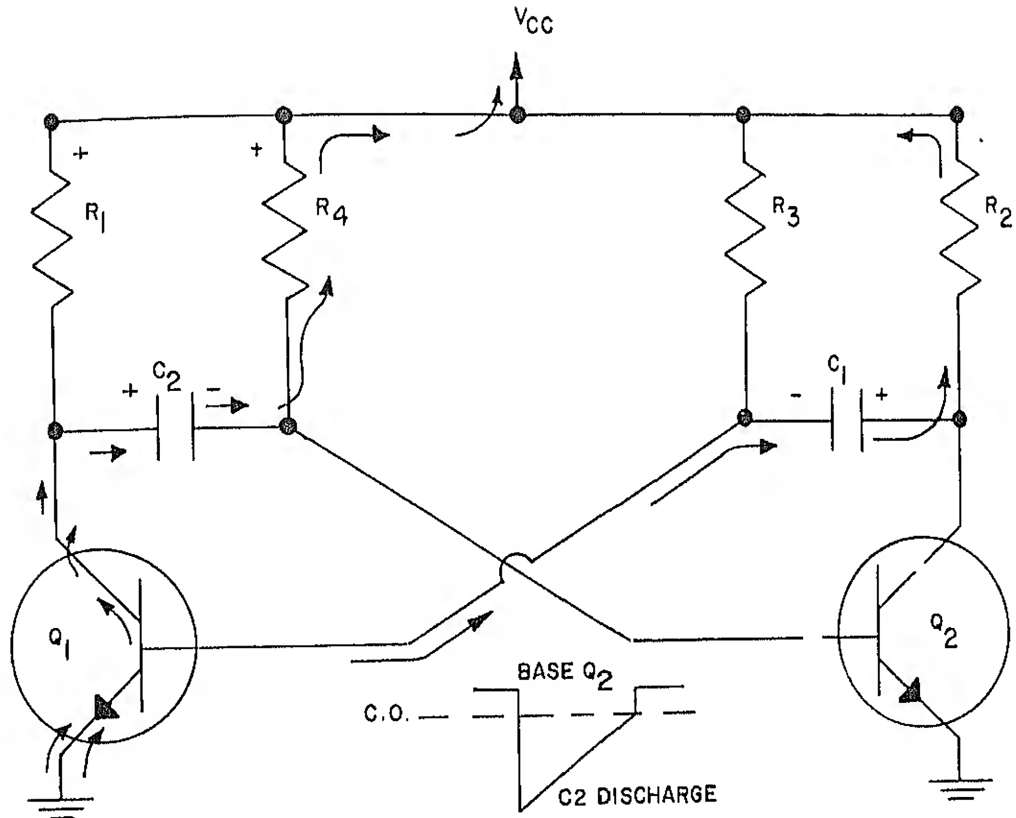


FIGURE 2 - Circuit charges.

C_2 discharges through R_4 and the forward-conducting resistance of Q_1, which keeps Q_2 cut off. As C_2 discharges, the base voltage of Q_2 rises toward cutoff. Q_2 starts conducting (refer to figure 3), its collector becomes negative and drives Q_1 into cutoff. As Q_1 goes into cutoff, its collector becomes positive. The change is coupled to the base of Q_2, driving it into maximum conduction. As the collector of Q_1 becomes positive, it causes C_2 to charge through R_1 and the emitter-base resistance of Q_2.

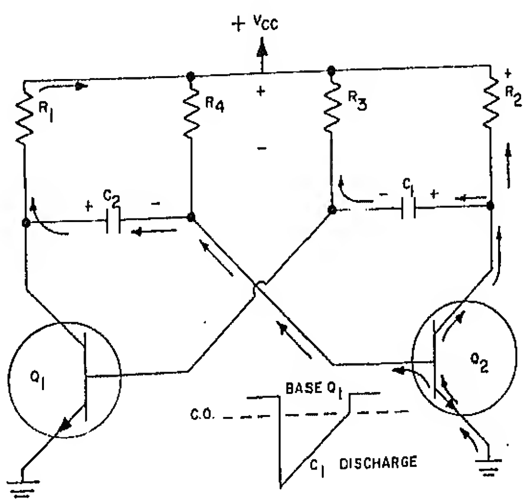


FIGURE 3 Circuit discharges

C_1 discharges through R_3 and the conducting resistance of Q_2. Refer to figure 4. The pulse width of the output waveform depends upon the RC time in the base circuit and how long each transistor is cut off.

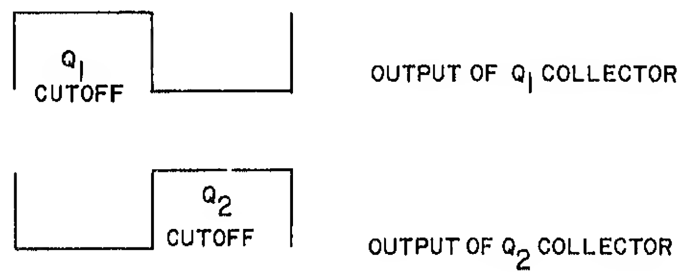


FIGURE 4 - Output waveform.

If R_1 equals R_2, R_3 equals R_4, C_1 equals C_2, and Q_1 Q_2 are matched, then the output waveform will be a symmetrical waveform. The negative time duration equals the positive time.

Effects of varying elements in a multivibrator

Figure 5 shows the effects when using NPN transistors. By returning the bases of the transistors back to V_{CC}, frequency stability is improved.

One-shot multivibrator

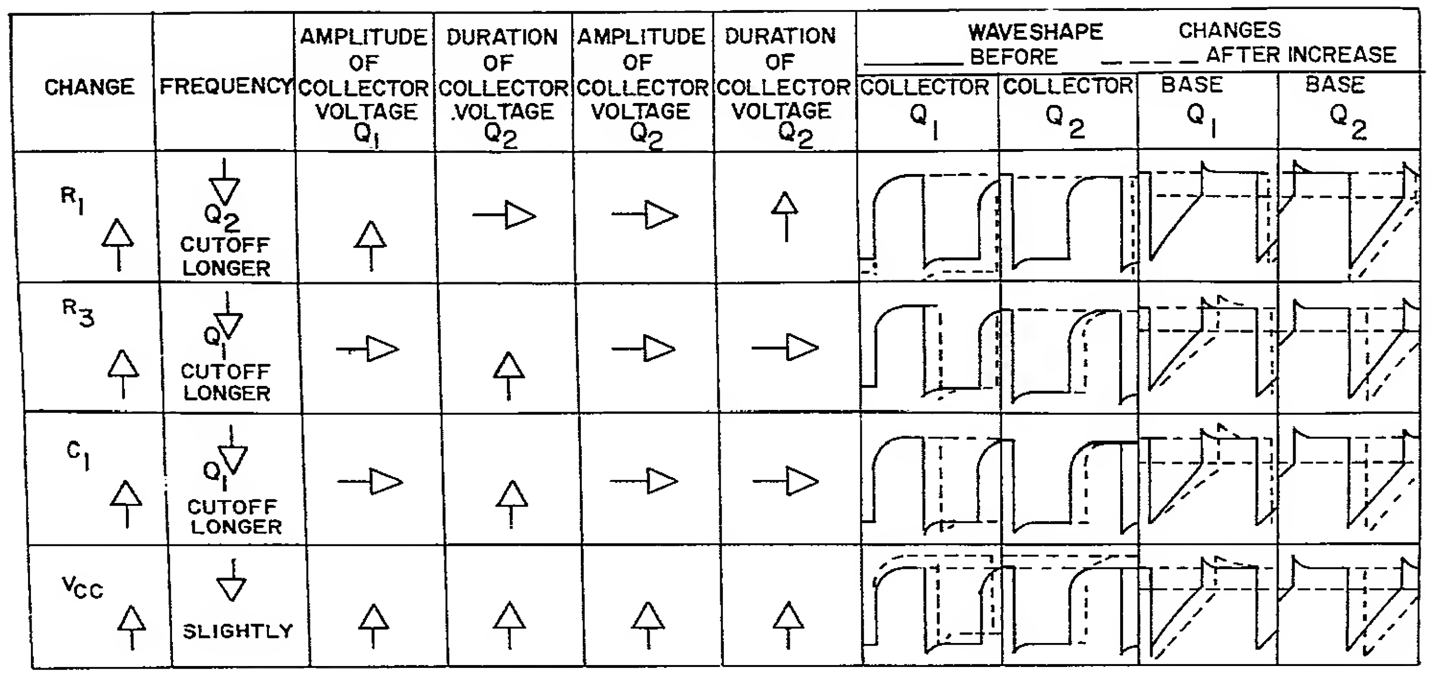


FIGURE 5 - Effects of varying elements in a multivibrator.

Figure 6 shows a typical circuit.

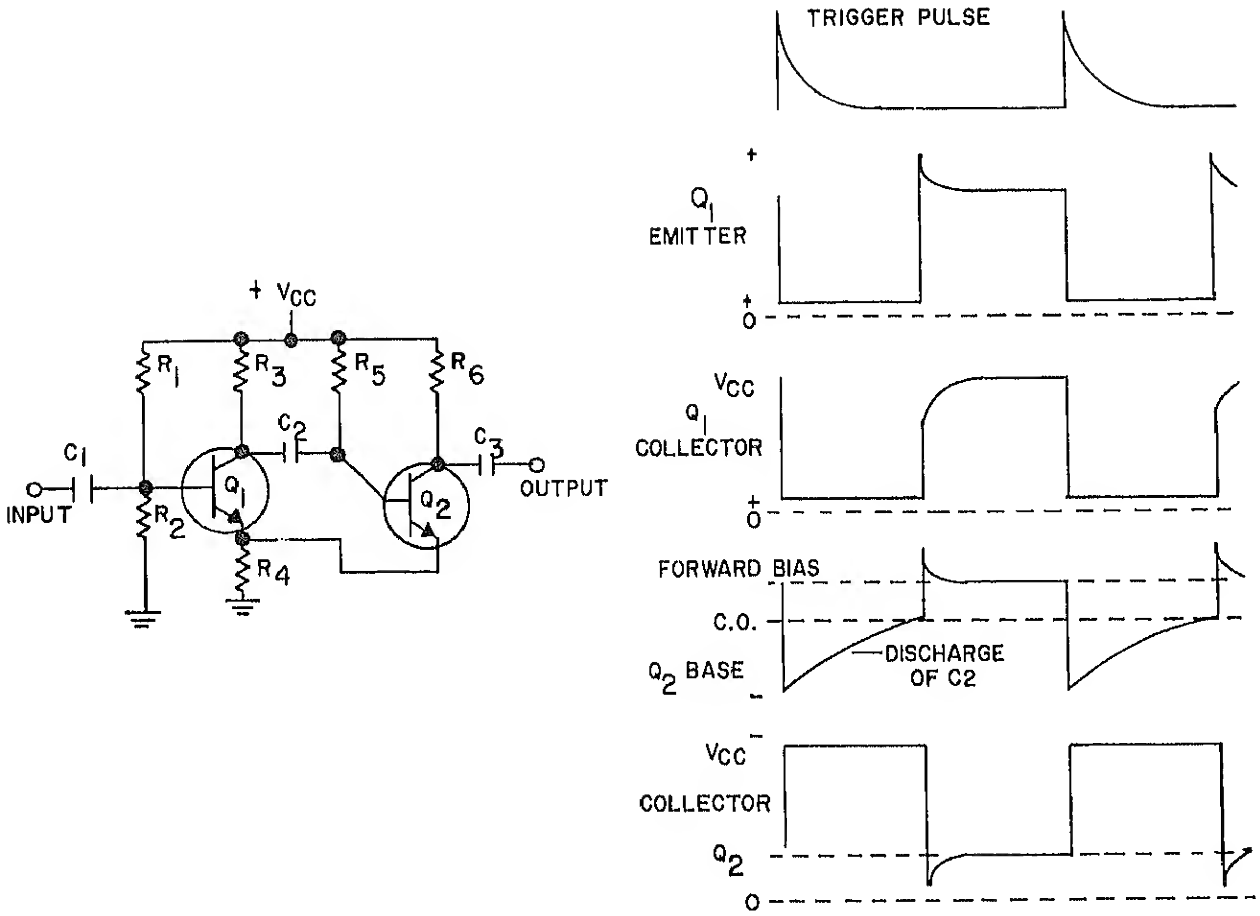


FIGURE 6 - Typical circuit.

The one-shot multivibrator (refer to figure 6) is a two-stage resistance-capacitance-coupled amplifier with one transistor cut off and one transistor conducting normally. The condition set up by the biasing arrangement for the transisotrs is Q_1 normally cut off with Q_2 conducting.

Circuit operation (refer to figure 7)

A positive trigger pulse to the base of Q_1 will cause Q_1 to conduct and cause the collector of Q_1 to become less positive. This change is coupled through C_2 and drives the base of Q_2 beyond cutoff. The negative going voltage on the collector of Q_1 causes C_2 to discharge through R_5, R_4, and the forward-conducting resistance of Q_2. C_2 discharge until Q_2's base reaches cutoff, at which time Q_2 begins to conduct. More current flows through R_4, which causes Q_1's emitter to become positive, reverse-biasing Q_1. R_1's and R_2's voltage divide V_{CC} and place a constant voltage on the base of Q_1, which is negative in respect to the emitter. This cuts Q_1 off. Q_2 is conducting with a low voltage on the collector. When Q_2 is cut off, the collector goes to V_{CC}.

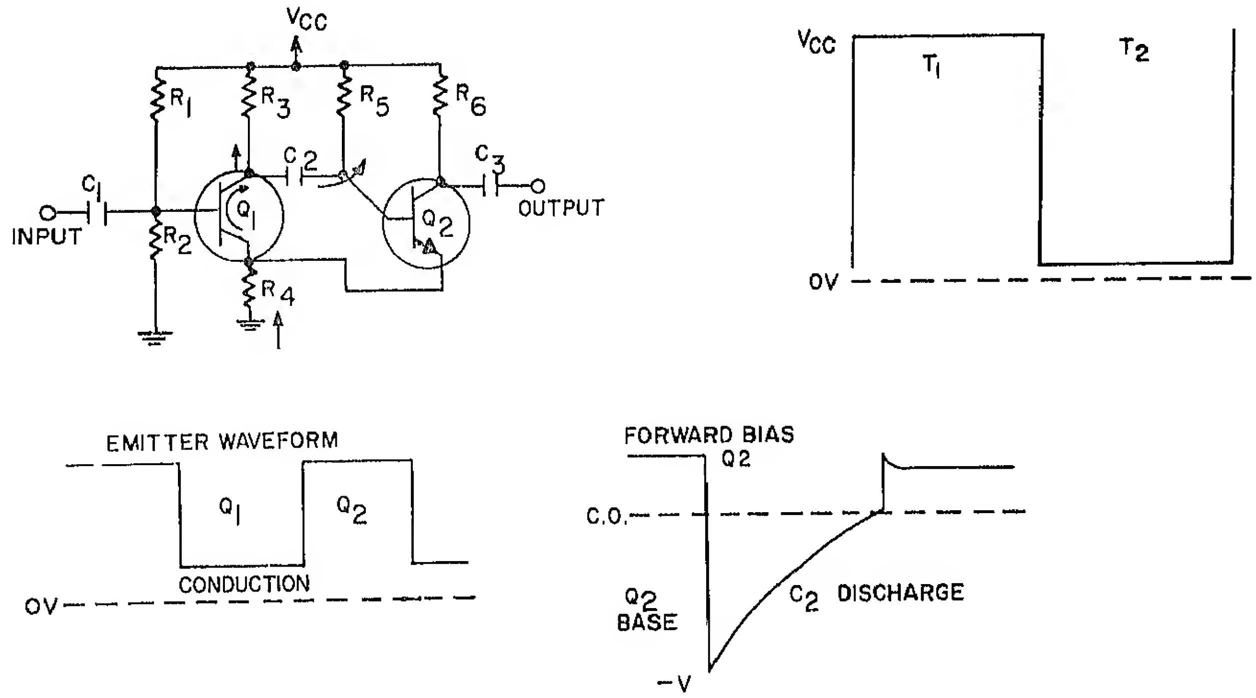


FIGURE 7 - Circuit operation.

The output frequency (refer to waveforms in figures 6 and 7) depends upon the input frequency and how long Q_2 is cut off. The time Q_2 is cut off, depends upon the RC time of R_5 and C_2, the amplitude of the signal developed across R_3, and the amplitude of the reverse-bias voltage felt on its base.

Figure 8 shows the effect of varying the elements of the one-shot multivibrator.

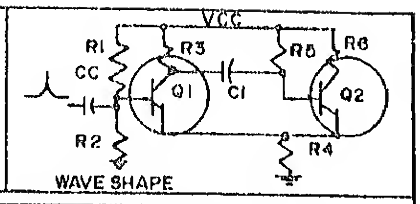
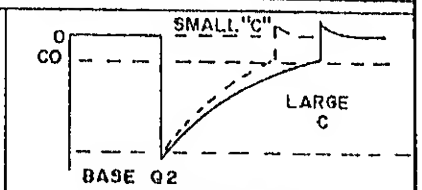
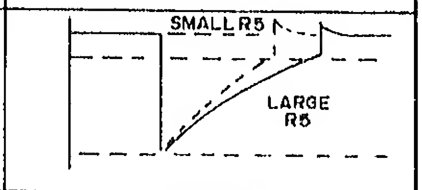
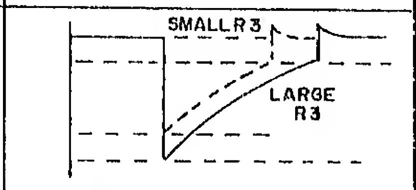
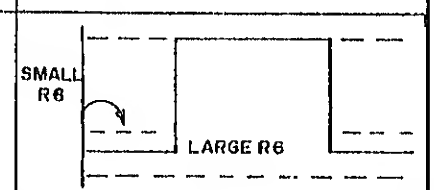
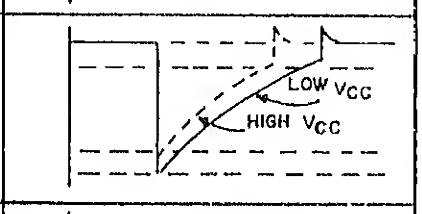
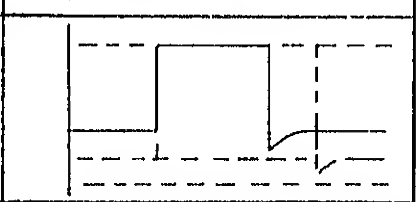
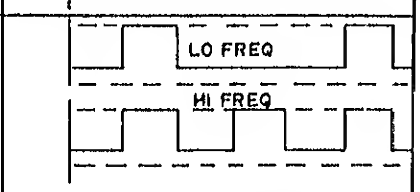
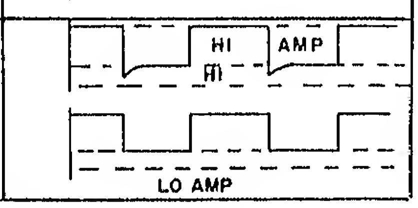
CIRCUIT CHANGE	EFFECT ON DURATION OF OUTPUT PULSE	EFFECT ON AMPLITUDE OF OUTPUT PULSE	EFFECT ON FREQUENCY OF PULSE REPETITION	EFFECT ON STABILITY	
INCREASE CI	INCREASED BECAUSE DISCHARGE LAST LONGER	NO CHANGE	NO CHANGE FREQUENCY GOVERNED BY TRIGGER FREQUENCY	NO CHANGE SAME % OF RC TIME USED	
INCREASE R5	INCREASE DISCHARGE IS SLOWER	NO CHANGE	NO CHANGE	NO CHANGE SAME %RC USED	
INCREASE R 3	INCREASE BECAUSE AMPLITUDE E_{CI} IS INCREASED	NO CHANGE	NO CHANGE	DECREASED BECAUSE DISCHARGE CURVE HAS LESS SLOPE @ CUT OFF	
INCREASE R6	NO CHANGE	INCREASED	NO CHANGE	NO CHANGE	
INCREASE Vcc	INCREASE	INCREASE	NO CHANGE	IMPROVED SLIGHTLY	
INCREASE R4	SHORTER	NO	NO	DECREASE	
INCREASE TRIGGER FREQUENCY	NO CHANGE UP TO POINT WHERE DURATION IS TIME BETWEEN PULSE	NO CHANGE	INCREASE	NO CHANGE	
INCREASE TRIGGER AMPLITUDE	NO CHANGE	NO CHANGE	NO CHANGE	IMPROVE SLIGHTLY	

FIGURE 8 - VARYING ELEMENTS IN ONE SHOT MULTIVIBRATOR

Bistable multivibrator

The bistable multivibrator has two stable states:

1. Q_1 conducting and Q_2 cut off.

2. C_2 conducting and Q_1 cut off.

It is also called a flip-flop or an Eccles-Jordan multivibrator. Figure 9 shows a transistorized flip-flop circuit:

1. R_1, R_3, and R_6 bias Q_2.

2. R_2, R_4, and R_5 bias Q_1.

3. R_1 is a collector resistor for the input of transistor Q_2.

4. R_2 is a collector resistor for the output of transistor Q_2.

5. C_1 and C_2 are quick-coupling capacitors.

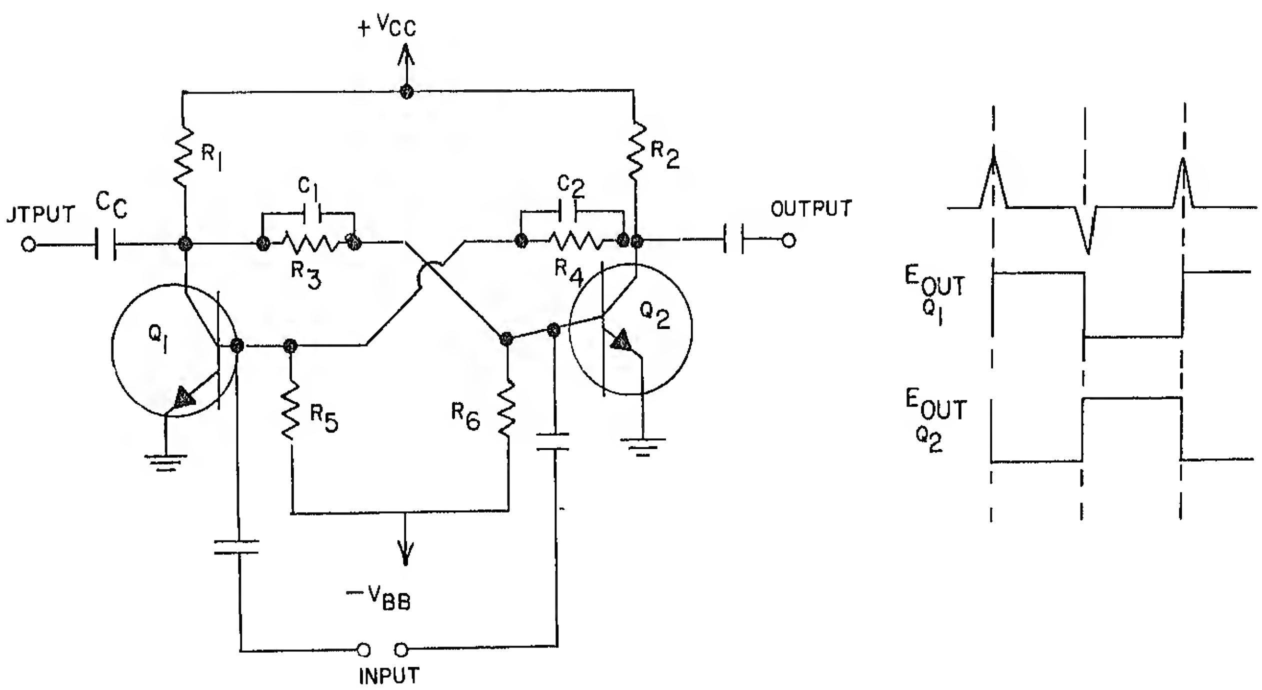


FIGURE 9 - Transistorized flip-flop circuit.

Circuit operation (refer to figure 9)

Assume that Q_1 is conducting. The collector voltage of Q_1 decreases, which places a negative voltage on the base of Q_2 through R_3, holding Q_2 cut off. The collector of Q_2 is positive, placing a positive voltage on the base of Q_1, keeping it in conduction. A negative trigger onto the base of Q_1 will cause Q_1's collector to go positive. This charge is quick-coupled to the base of Q_2, which causes Q_2 to conduct, causing its collector to go in a negative direction. This negative change is coupled to the base of Q_1, causing Q_1 to decrease conduction further. This action continues until Q_1 goes into cutoff and Q_2 goes into saturation. The multivibrator will stay in this state until the next input trigger. The output frequency is dependent upon the input frequency. If the circuit is fed with trigger pulses of the same polarity, the output will be a two-to-one countdown; i.e., two triggers in and one cycle out.

Schmitt trigger

General information

The Schmitt trigger is primarily used to supply a square-wave output, when triggered by a sine wave, sawtooth, or other irregularly shaped waveform. It is also known as a squaring multivibrator or an emitter-coupled bistable multivibrator. The Schmitt trigger circuit differs from the conventional bistable multivibrator circuit in that one of the coupling (feedback) networks is replaced by a common-emitter resistor. The additional regenerative feedback developed by the common-emitter-coupling arrangement provides quicker action and straighter leading and trailing edges on the output waveform than in other multivibrators. Because of the relatively instantaneous switching action of this arrangement, the waveform of the input trigger has no effect on the output so that essentially square-wave output signals are always produced.

Characteristics

1. The Schmitt trigger uses self- or fixed-bias.

2. The Schmitt trigger provides an output gate, regardless of the input waveform.

e Schmitt trigger uses two PNP or NPN transistors in a mmon-emitter configuration.

llector-to-base feedback provides one switching path, while mmon-emitter-coupling feedback provides the other switching th.

Basic circuit operation

Component identification (see figure 10)

1. R_1 is a collector load resistor for the input transistor Q_1.

2. R_2 is the collector load resistor for the output transistor Q_2 and is used to develop the output.

3. R_3 is the feedback resistor from Q_1 collector to Q_2 base.

4. R_4 is the feedback (coupling) resistor that is common to both emitters. It is used to improve waveshaping.

5. C_1 is a feedback capacitor, which bypasses resistor R_3 to help speed up switching action.

Initially, transistor Q_2 conducts heavily because of the large forward bias supplied by the voltage divider, consisting of collector resistor R_1, feedback resistor R_3, and base resistor R_5 series-connected between V_{CC} and ground. Q_1 is reverse-biased by the voltage developed across the common emitter resistor R_4 by Q_2's current flow.

Assume now, a sine wave input signal applied. During the positive half-cycle of operation, the positive input voltage on the base keeps Q_1 reverse-biased so that it cannot conduct. Since in this condition, the output is developing a positive signal, it is evident that the input and output are in phase.

When the input becomes negative, the base of Q_1 is driven negative and Q_1 becomes forward-biased. Q_1 begins to conduct and current flows through R_1. As the potential at the collector decreases (becomes less negative), this change, coupled to the base of transistor Q_2, reduces Q_2's conduction. The emitter current of Q_2 decreases, lowering the potential across resistor R_4. The emitter of transistor Q_1 becomes less negative, reducing the reverse bias and increasing collector current. The regenerative action continues until transistor Q_1 is operating in the saturation region and transistor Q_2 is cut off. The output voltage is at maximum negative (V_{CC}).

The new stable condition continues until the input begins to rise (become more positive). The positive-going input decreases the base potential of Q_1 and decreases forward bias. The collector voltage increases (becomes more negative); emitter current decreases, decreasing the potential across R_4. Simultaneously, the increasing (negative) voltage at the collector of transistor Q_1 is coupled to the base of transistor Q_2, driving it negative; and the decreasing voltage across R_4 causes the emitter of transistor Q_2 to become more positive. Both actions tend to forward-bias the emitter-base junction of Q_2, and it begins to conduct. As transistor Q_2 conducts, the emitter current flowing through R_4 increases the voltage drop across R_4, making the emitter of Q_1 more negative.

The negative-going voltage on Q_1's emitter decreases the forward bias, and decreases the conduction of Q_1. This regenerative action continues until Q_1 is cut off and Q_2 is conducting. The circuit is now back in its initial stable condition.

Once started, the switching action is quickly accomplished, because of the extreme regenerative action of the emitter-coupled circuit. The rise-and-fall time of the output wave of this circuit is shorter than that of the conventional bistable multivibrator. The shape of the output wave does not depend on the shape of the input wave. The width of the output waveform is controlled by the difference in time between the off-and-on reference levels. When the input waveform is symmetrical and equal, a true square wave is produced.

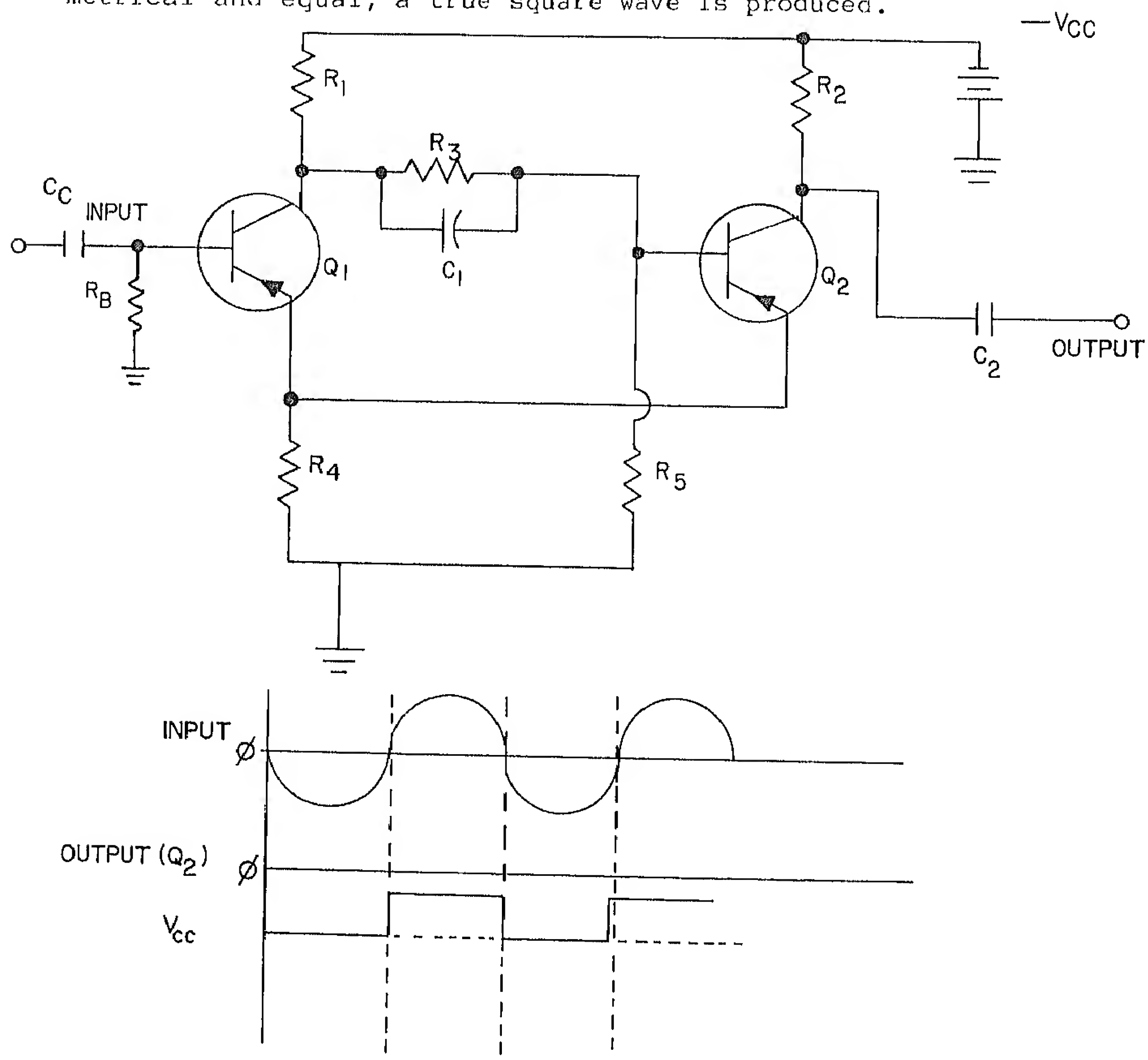


FIGURE 10 - Components of Schmitt trigger and waveforms.

NOTETAKING SHEET 3.12.IN

MULTIVIBRATORS

REFERENCES:

1. Basic Electronics, Vol. II. NAVPERS 10087-C. Chapter 3, pages 45 to 67.

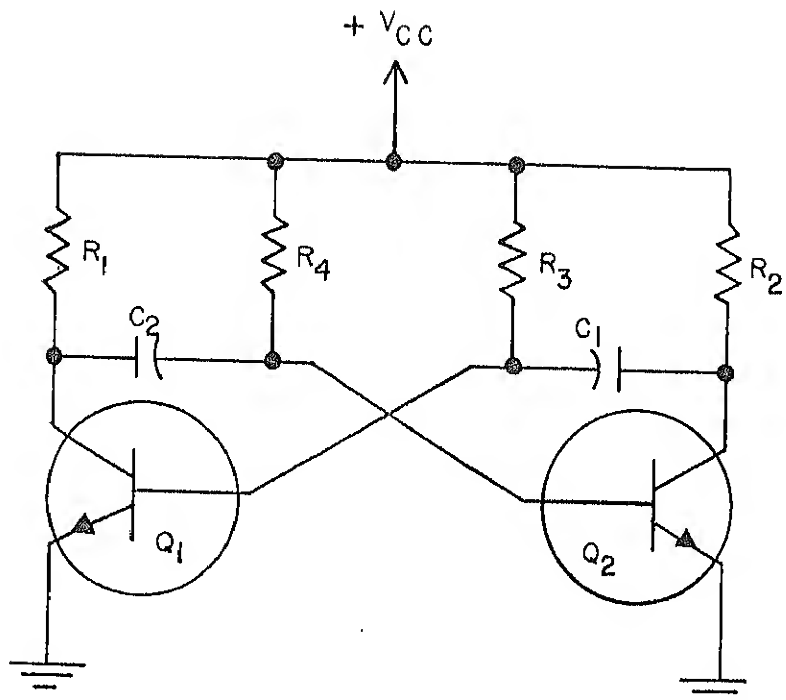
2. Electronic Circuit Analysis, Vol. I. NAVAIR 00-80-T-79. Chapter 6, pages 6-56 to 6-79.

3. Electronic Circuits. NAVSHIPS 0967-000-0120. Chapter 7, pages 7-1 to 7-64.

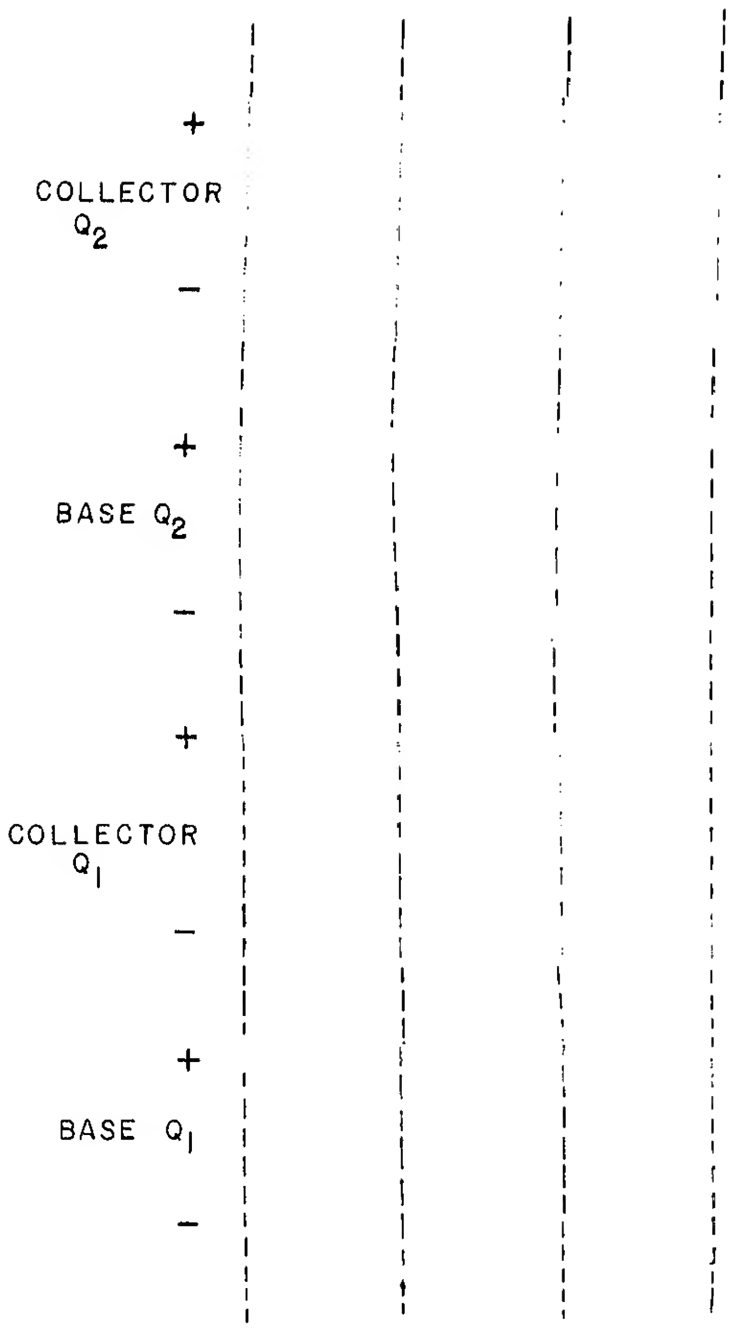
NOTETAKING OUTLINE:

A. General Information

B. Astable Multivibrator



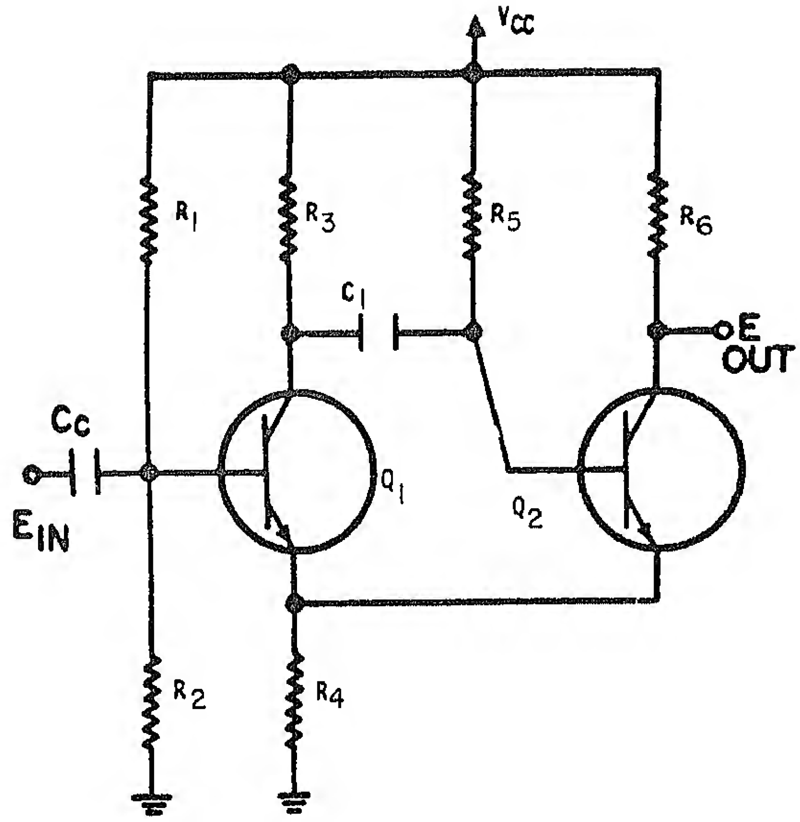
ASTABLE MULTIVIBRATOR



ASTABLE MULTIVIBRATOR WAVEFORMS

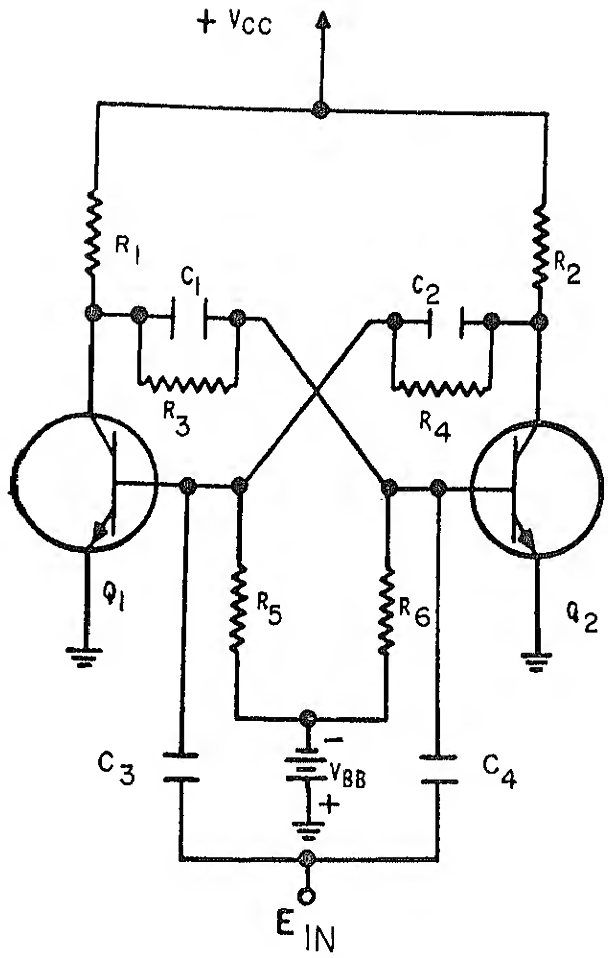
C. Monostable Multivibrator

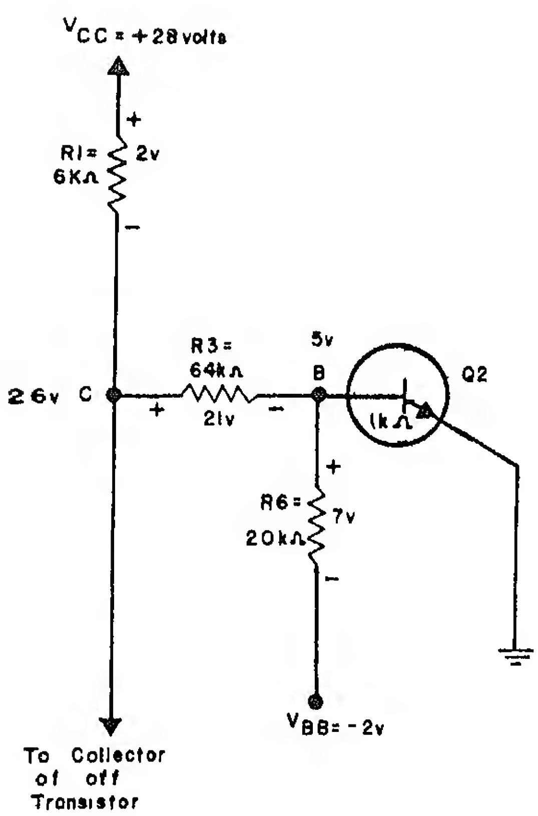
MONOSTABLE MULTIVIBRATOR

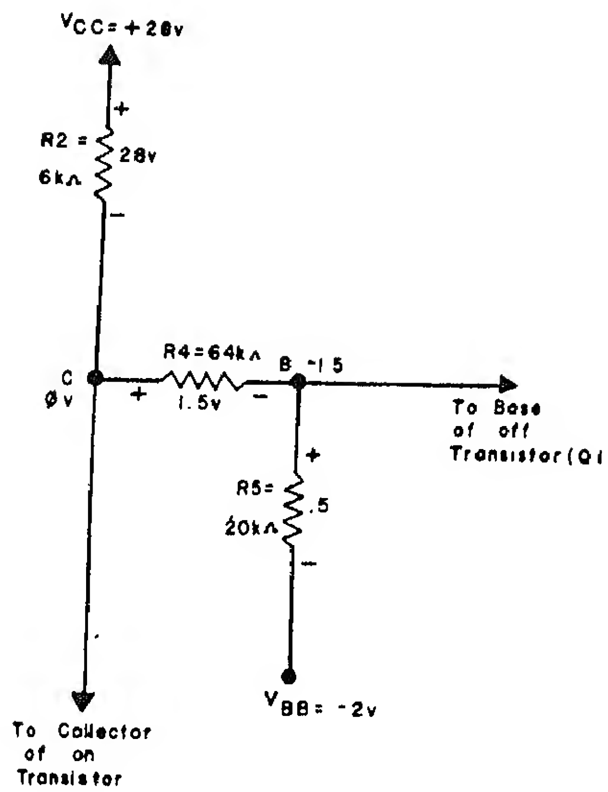


D. Bistable Multivibrator (Eccles-Jordan)

BISTABLE MULTIVIBRATOR

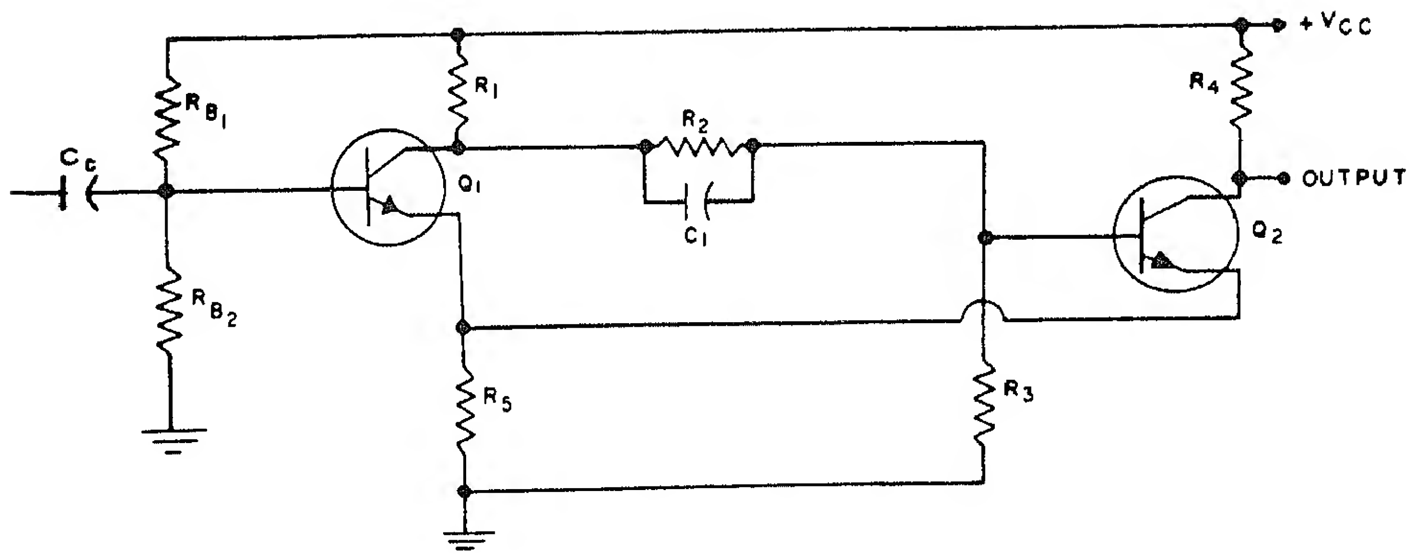






E. Schmitt-trigger Multivibrator

SCHMITT TRIGGER MULTIVIBRATOR



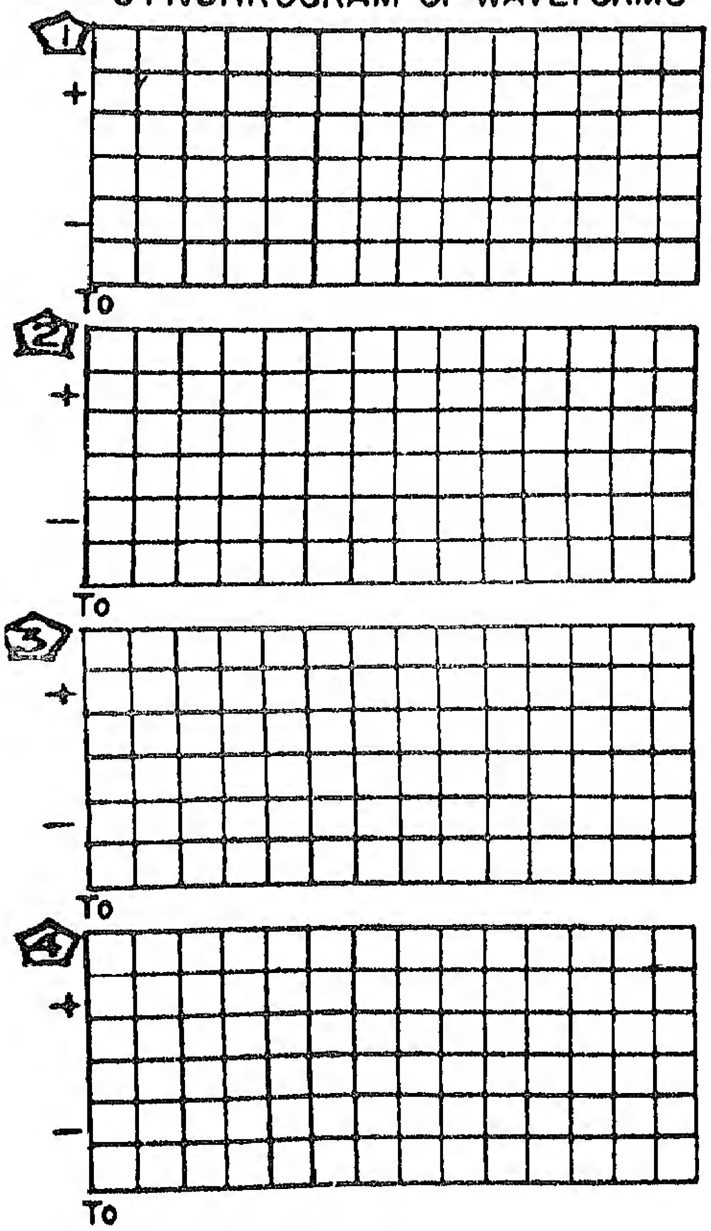
NOTETAKING SHEET 3.12.2N

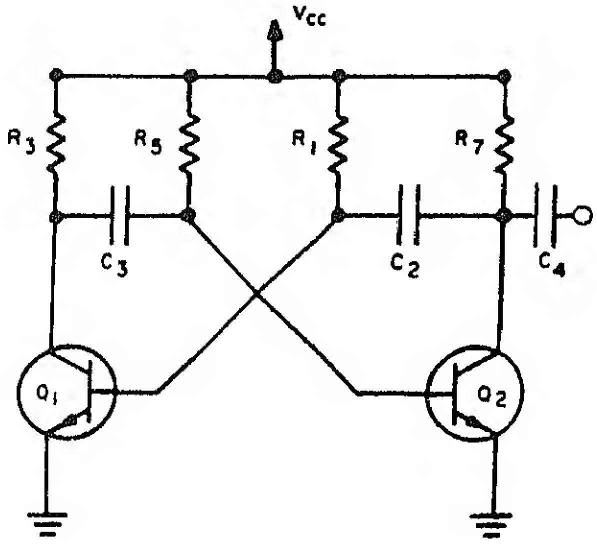
MULTIVIBRATOR OPERATION

F. Free-running (astable) Multivibrator Operator

Record all data and waveforms as the instructor indicates throughout the lecture demonstration. Label each waveform.

SYNCHROGRAM OF WAVEFORMS





FREE-RUNNING MULTI-VIBRATOR

NOTES:

STUDY QUESTIONS

1. The output frequency of a free-running multivibrator is primarily controlled by ______________________.

NOTE: Refer to the free-running multivibrator schematic in answering questions 2-4.

2. The charge path for C_3 is ______________________

______________________.

3. Decreasing the value of C_2 will cause the __________ PW to decrease, the __________ PW will remain the same, the PRT will ______________ and the PRF will ______________.

4. Increasing R5 and R1 to twice their value will cause the positive and negative pulse widths to ______________, the PRT to __________ and the PRF to ______________.

5. Describe the basic operation of a free-running multivibrator.

____

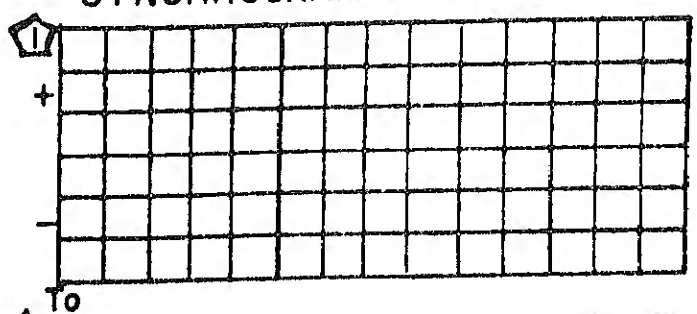
______________________.

Effect of changing component values.

or

SYNCHROGRAM OF WAVEFORMS

INCREASE C_3



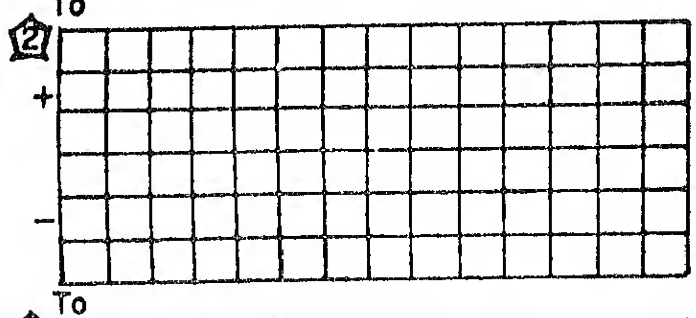
+PW ______

−PW ______

PRT ______

PRF ______

INCREASE C_2



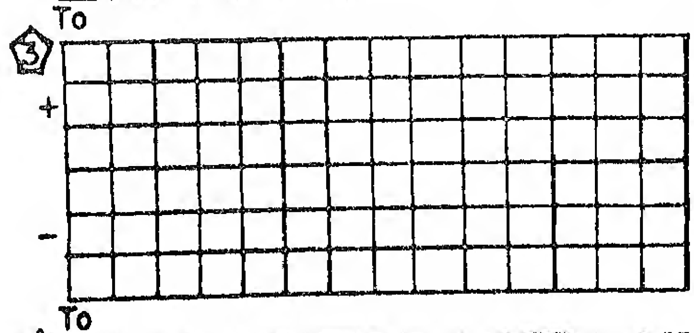
+PW ______

−PW ______

PRT ______

PRF ______

INCREASE C_2 & C_3



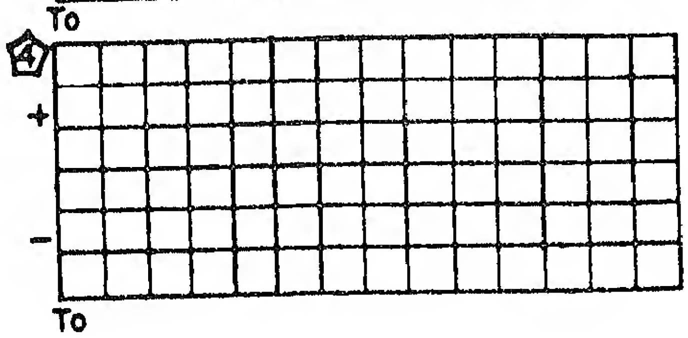
+PW ______

−PW ______

PRT ______

PRF ______

DECREASE R_5



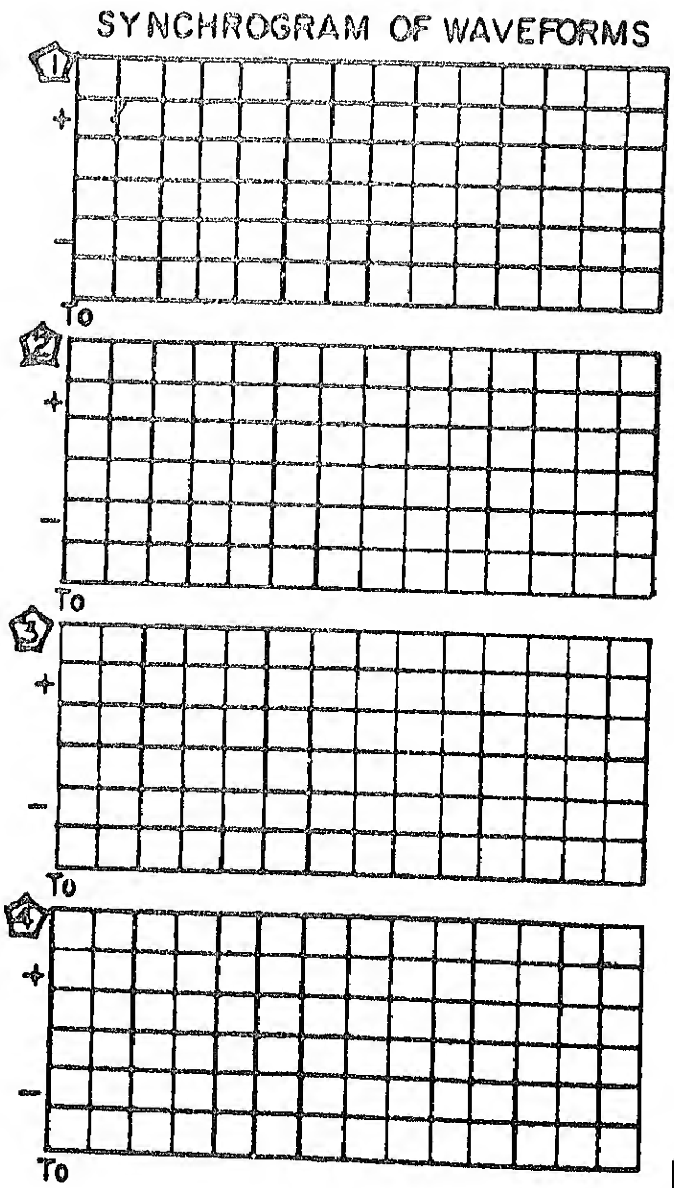
+PW ______

−PW ______

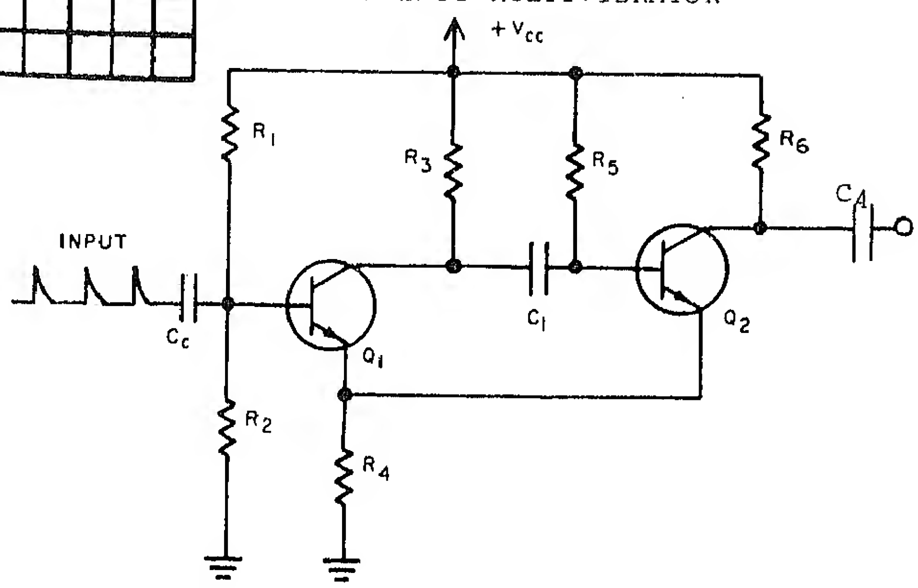
PRT ______

PRF ______

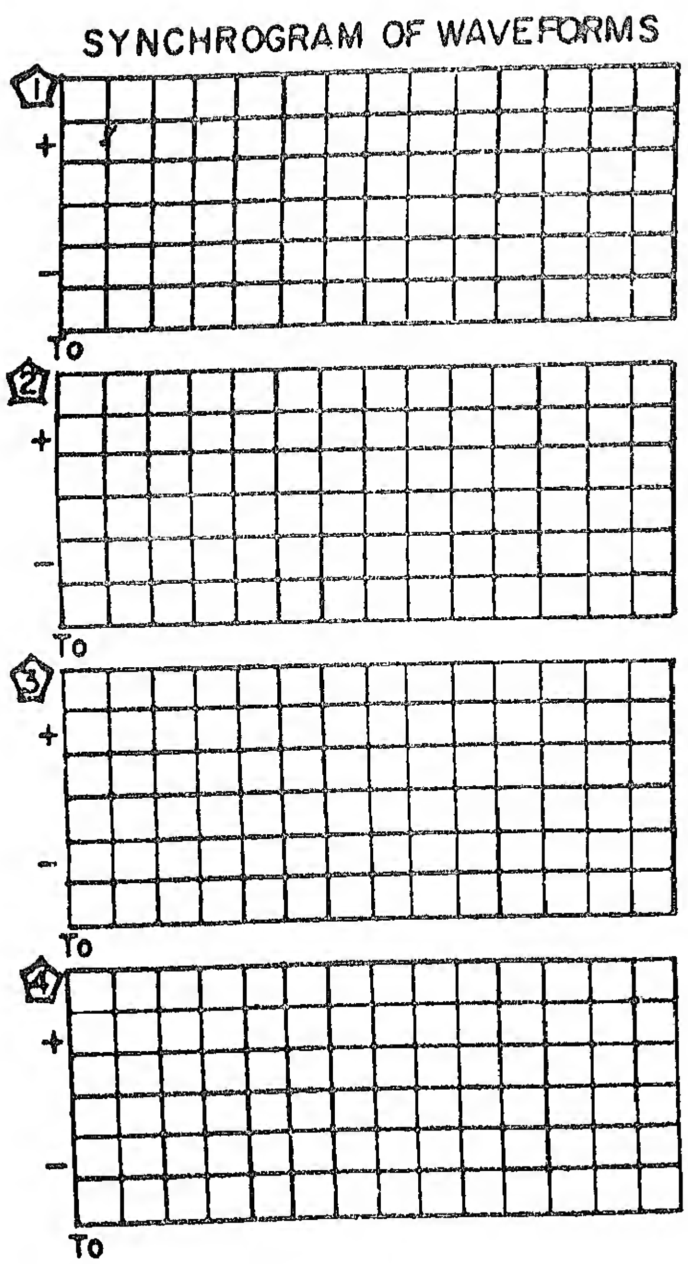
G. One-shot Multivibrator (Monostable) Operation



ONE-SHOT MULTIVIBRATOR



Effect of changes in RCT and frequency



NORMAL

+PW ______

-PW ______

PRT ______

PRF ______

INCREASE C_3

+PW ______

-PW ______

PRT ______

PRF ______

DECREASE R_5

+PW ______

-PW ______

PRT ______

PRF ______

DECREASE INPUT FREQUENCY

NOTES:

STUDY QUESTIONS

1. The output frequency of a one-shot multivibrator is primarily controlled by the ________________.

2. The positive PW of the one-shot is primarily controlled by the ________________.

NOTE: Refer to the one-shot multivibrator schematic in answering questions 3 and 4.

3. The charge path for C_3 is ________________.

4. Increasing the value of R_5 will cause the positive PW to ________, the negative PW will ________, the PRT will ________ and the PRF will ________.

5. Describe the basic operation of a one-shot multivibrator.

____

____.

APPENDIX A

UNIT III FORMULA SHEET

UNIT III FORMULA SHEET

I. POWER SUPPLIES

A. A-c voltage relationships

1. $E_{pk} = (1.414)E_{rms})$ or $\frac{E_{rms}}{0.707}$

2. $E_{rms} = (E_{pk})(0.707)$ or $\frac{E_{pk}}{1.414}$

B. Transformer relationships

1. $TR = \frac{N_p}{N_s} = \frac{E_p}{E_s} = \frac{I_s}{I_p} = \sqrt{\frac{Z_p}{Z_s}}$

2. $Z_p = (TR)^2(Z_s)$

C. Rectifiers

1. Output d-c voltages with resistive load or inductor-input filter

a. Half-wave and full-wave rectifiers

$E_{d-c} = (0.45)(E_{sec})$ (Preferred)

b. Bridge rectifiers

$E_{d-c} = (0.9)(E_{sec})$ (Preferred)

2. Output d-c voltages with capacitor-input filters

a. Half-wave and bridge rectifiers

$E_{d-c} = E_{sec\ pk}$ (Approximation/preferred)

b. Full-wave rectifiers

$E_{d-c} = (1/2)(E_{sec\ pk})$ (Approximation/preferred)

3. Voltage doublers (half-wave and full-wave)

$E_{d-c} = (2)(E_{sec\ pk})$ (Approximation/preferred)

D. Filters

1. Percentage of ripple = $\frac{E_{rip}}{E_{d-c}} \times 100$

2. E_{d-c} at "B" = $E_{R_L} = \frac{(E_{d-c} \text{ at "A"})(R_L)}{R_L + R_C}$ (Preferred)

3. E_{d-c} at "B" = E_{R_L} = (Of the choke)
(E_{d-c} at "A") - IR drop

4. E_{rip} at "B" = $E_{X_C} = \frac{(E_{rip} \text{ at "A"})(X_C)}{X_L - X_C}$ (Preferred)

5. $\frac{(E_{rip} \text{ at "A"})}{(E_{rip} \text{ at "B"})} = \frac{X_L}{X_C}$ (Approximation)

6. Percentage of regulation = $\frac{E_{no\ load} - E_{full\ load}}{E_{full\ load}} \times 100$

II. POWER AMPLIFIERS

A. Input power d-c

1. Collector power d-c = $(I_C)(V_{CE})$

2. Collector circuit power d-c = $(I_C)(V_{CC})$

3. Circuit power d-c = $(I_{CC})(V_{CC})$

B. Efficiency

1. Percentage of efficiency = $\frac{P_{a-c}}{P_{d-c}}$ 100

2. Percentage of collector efficiency = $\frac{P_{a-c}}{(I_C)(V_{CE})} \times 100$

3. Percentage of collector ckt. efficiency

$= \frac{P_{a-c}}{(I_C)(V_{CC})} \times 100$

4. Percentage of circuit efficiency = $\frac{Pa_{-}c}{(ICC)(VCC)} \times 100$

III. CAPACITANCE AND RC TIME

A. Total capacitance

1. Series circuits

a. $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$, etc.

b. $C_T = \frac{(C1)(C2)}{(C_1) + (C_2)}$

2. Parallel circuits

$C_T = C1 + C_2 + C_3$, etc.

B. Charge in coulombs

1. $Q = (C)(E)$

2. $Q_T = Q_{C_1} + Q_{C_2}$, etc. (For parallel circuit)

3. $Q_T = (C_T)(E)$ (For a series circuit)

C. Kirchhoff's voltage law

$(E_a) + (E_C) + (E_R) = 0$

D. RC switching circuits

1. $T = RC$

2. $E_{effective} = E_R$

3. Five step method:

a. Find E_{eff} $[(E_a) + (E_C) + (E_R) = 0]$

b. Find the number of time constants:

No. of TC = $\frac{\text{switch time}}{\text{RC time}}$ Then convert to percentage of change from the chart

c. Find the change of E_C:

$\Delta E_C = (\%\Delta)(E_{eff})$

d. Find $E_{C\text{-}new} = (E_{Cold}) \pm (\Delta E_C)$

e. Find $E_{R\text{-}new} = [(E_a) + (E_{Cnew}) + (E_R) = 0]$

IV. INDUCTANCE AND L/R TIME

A. Total inductance

1. Series circuit:

a. $L_T = L_1 + L_2 + L_3$, etc. (NO coupling)

b. $L_T = L_1 + L_2 \pm 2M$ (WITH coupling

2. Parallel circuit:

a. $\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$, etc.

b. $L_T = \frac{L_1 \times L_2}{L_1 + L_2}$

B. Inductance

$$L = \frac{1.257\ \mu N^2\ S}{10^8\ L}$$

C. Mutual inductance

$$M = K\ \sqrt{L_p L_s}$$

D. Coefficient of couplings

$$K = \sqrt{K_p K_s}$$

E. Rate of change of current

$$\left(\frac{\Delta i}{\Delta t}\right) = \frac{EL}{L} \qquad E_L = L\left(\frac{\Delta i}{\Delta t}\right)$$

F. L/R switching circuit

1. $T = L/R$

2. Find I_{max}

3. Find the number of time constants:

No. of TC $= \frac{\text{switch time}}{\text{L/R time}}$ Then convert to percentage of change from the chart.

4. $\Delta I = (\%\Delta)(I_{max})$

5. $I_{new} = (I_{old}) \pm (\Delta I)$

6. Find $E_{Rnew} = (R)(I_{new})$

7. Find $E_L = [(E_a) + (E_{Rnew}) + (E_L) = 0]$

V. NONSINUSODIAL WAVEFORMS

A. D-c average of a square wave and a triangular wave (back-to-back sawtooth).

$$d\text{-}c_{avg} = \frac{(\Delta E)(P.P.W.)}{(PRT)} + (E_{base})$$

B. D-c average of a sawtooth with rest time and a continuous sawtooth

$$d\text{-}c_{avg} = \frac{(\Delta E)(P.P.W.)}{2\ (PRT)} + (E_{base})$$

VI. WAVESHAPING CIRCUITS

A. $i = \frac{(\Delta e)(C)}{(\Delta t)}$

B. $e_{r_{max}} = \frac{(\Delta e)(RC)}{(\Delta t)}$

VII. SWEEP GENERATORS

A. General

1. Rate of change $= \frac{E_{effective}}{RC\ time}$

2. $\%\Delta = \frac{\Delta E_C}{E_{effective}} \times 100$

3. $PW = (No.\ of\ TC)(RCT)$

B. U.J.T. sweep generators

1. $V_{B_2B_1} = \frac{(V_{BB})(R_{BB})}{R_{BB} + R_2}$

2. $f_p = V_p = (nV_{B_2B_1}) + V_D$

3. $E_{effective} = V_{EE} - E_{extinguishing}$

4. $\Delta E_C = f_p - E_{extinguishing}$

C. S.C.R. sweep generators

1. No. of TC $= \frac{PRT\ of\ triggers}{RC\ time}$

2. $V_{TO} = V_{turn\ off} = E_{extinguishing}$

3. $E_{effective} = E_a - V_{TO}$

VIII. LIMITERS

E_R drop = $(d\text{-}c_{avg\text{-}in}) - (d\text{-}c_{avg\text{-}out})$

IX. CLAMPERS

A. $E_C = (E_{pk\text{-}in}) - (E_{pk\text{-}out})$

B. $E_C = (E_{base\text{-}in}) - (E_{base\text{-}out})$

C. $E_C = (d\text{-}c_{avg\text{-}in}) - (d\text{-}c_{avg\text{-}out})$

RC PERCENTAGE CHANGE TABLE

No. RC	% Change	% Remain	No. RC	% Change	% Remain	No. RC	% Change	% Remain
0.05	4.877	95.123	1.05	65.006	34.994	2.05	87.127	12.873
0.10	9.516	90.484	1.10	66.713	33.287	2.10	87.754	12.246
0.15	13.929	86.071	1.15	68.336	31.664	2.15	88.352	11.648
0.20	18.127	81.873	1.20	69.881	30.119	2.20	88.920	11.080
0.25	22.120	77.880	1.25	71.350	28.650	2.25	89.460	10.540
0.30	25.918	74.082	1.30	72.747	27.253	2.30	89.974	10.026
0.35	29.531	70.469	1.35	74.076	25.924	2.35	90.463	9.536
0.40	32.968	67.032	1.40	75.340	24.660	2.40	90.928	9.072
0.45	36.237	63.763	1.45	76.543	23.457	2.45	91.371	8.629
0.50	39.347	60.653	1.50	77.677	22.313	2.50	91.792	8.208
0.55	42.305	57.695	1.55	78.775	21.225	2.55	92.192	7.808
0.60	45.119	54.881	1.60	79.810	20.190	2.60	92.573	7.427
0.65	47.795	52.205	1.65	80.795	19.205	2.65	92.935	7.065
0.70	50.341	49.659	1.70	81.732	18.268	2.70	93.279	6.721
0.75	52.763	47.237	1.75	82.623	17.377	2.75	93.607	6.393
0.80	55.067	44.933	1.80	83.470	16.530	2.80	93.919	6.081
0.85	57.259	42.741	1.85	84.276	15.724	2.85	94.216	5.784
0.90	59.343	40.657	1.90	85.046	14.957	2.90	94.498	5.502
1.00	63.212	36.788	2.00	86.466	13.534	3.00	95.021	4.979
3.05	95.264	4.736	4.05	98.257	1.743	5.05	99.359	0.641
3.10	95.495	4.505	4.10	98.343	1.657	5.10	99.390	0.610
3.15	95.715	4.285	4.15	98.423	1.577	5.15	99.420	0.580
3.20	95.924	4.076	4.20	98.500	1.500	5.20	99.448	0.552
3.25	96.123	3.877	4.25	98.573	1.427	5.25	99.475	0.525
3.30	97.312	3.688	4.30	98.643	1.357	5.30	99.501	0.499
3.35	96.492	3.508	4.35	98.710	1.290	5.35	99.525	0.475
3.40	97.663	3.337	4.40	98.773	1.227	5.40	99.548	0.452
3.45	96.825	3.175	4.45	98.830	1.170	5.45	99.570	0.430
3.50	96.980	3.020	4.50	98.889	1.111	5.50	99.591	0.409
3.55	97.128	2.872	4.55	98.943	1.057	5.55	99.611	0.389
3.60	97.268	2.732	4.60	98.998	1.005	5.60	99.630	0.370
3.65	97.401	2.599	4.65	99.043	0.957	5.65	99.648	0.352
3.70	97.528	2.472	4.70	99.090	0.910	5.70	99.665	0.335
3.75	97.648	2.352	4.75	99.134	0.866	5.75	99.681	0.319
3.80	97.763	2.237	4.80	99.177	0.823	5.80	99.697	0.303
3.85	97.872	2.128	4.85	99.217	0.783	5.85	99.712	0.288
3.90	97.976	2.024	4.90	99.255	0.745	5.90	99.726	0.274
3.95	98.075	1.925	4.95	99.291	0.709	5.95	99.739	0.261
4.00	98.169	1.832	5.00	99.326	0.674	6.00	99.752	0.248

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0.70	50.341	49.659	1.70	81.732	18.268	2.70	93.279	6.721
0.75	52.763	47.237	1.75	82.623	17.377	2.75	93.607	6.393
0.80	55.067	44.933	1.80	83.470	16.530	2.80	93.919	6.081
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